Lecture 3: search for new physics

S.Xella

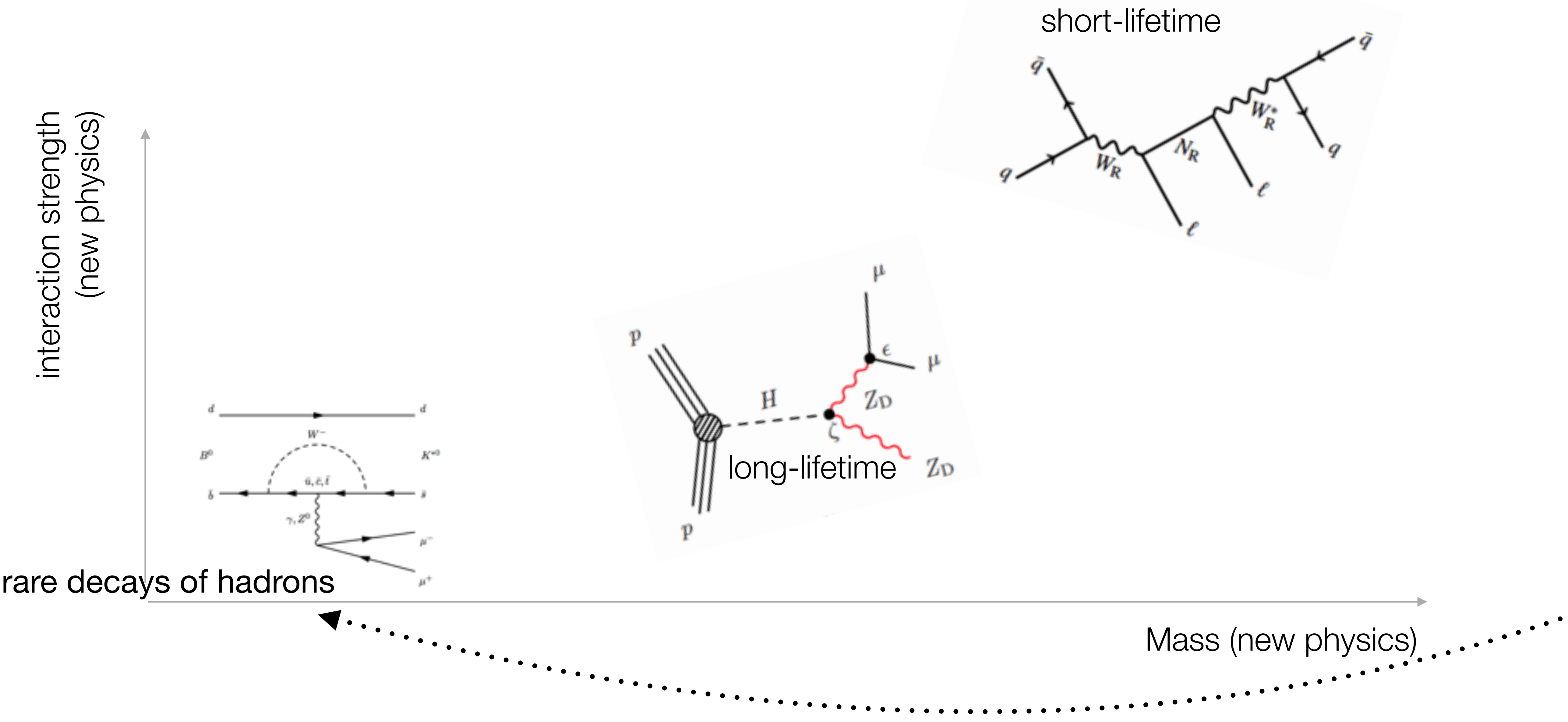
Otherwise formulated:

why ATLAS & CMS are called multipurpose detectors !

New physics: why ?

- Higgs boson was the last missing piece predicted by the Standard Model : observed in 2012 by ATLAS & CMS.
- **But** : even if the SM will pass all tests at the LHC, the Standard Model is NOT the complete theory of Nature
- Dark matter, baryogenesis, neutrino masses and oscillations : we have big observations to explain.
- New particles or new particle phenomena are most likely behind these extraordinary observations.
- Particle physics enters a new era, where theory is of limited guidance, and as many and as new and unconventional as possible experimental results need to be pursued.

How could new physics manifest to us?



interaction strength (new physics)

short-lifetime

long-lifetime

rare decays of hadrons

Mass (new physics)

Did we miss something?

- we have so far found only a handfull of tensions at the LHC. Not enough to point the way to the next step in understanding. We of course hope the next 3 years of analysis of all the data collected at the LHC (or elsewhere) pop up new interesting information.

- either we have not looked cleverly enough

    - so we must explore new search strategies, already from the trigger analysis level.

- or the new particles lie at an energy inaccessible to us

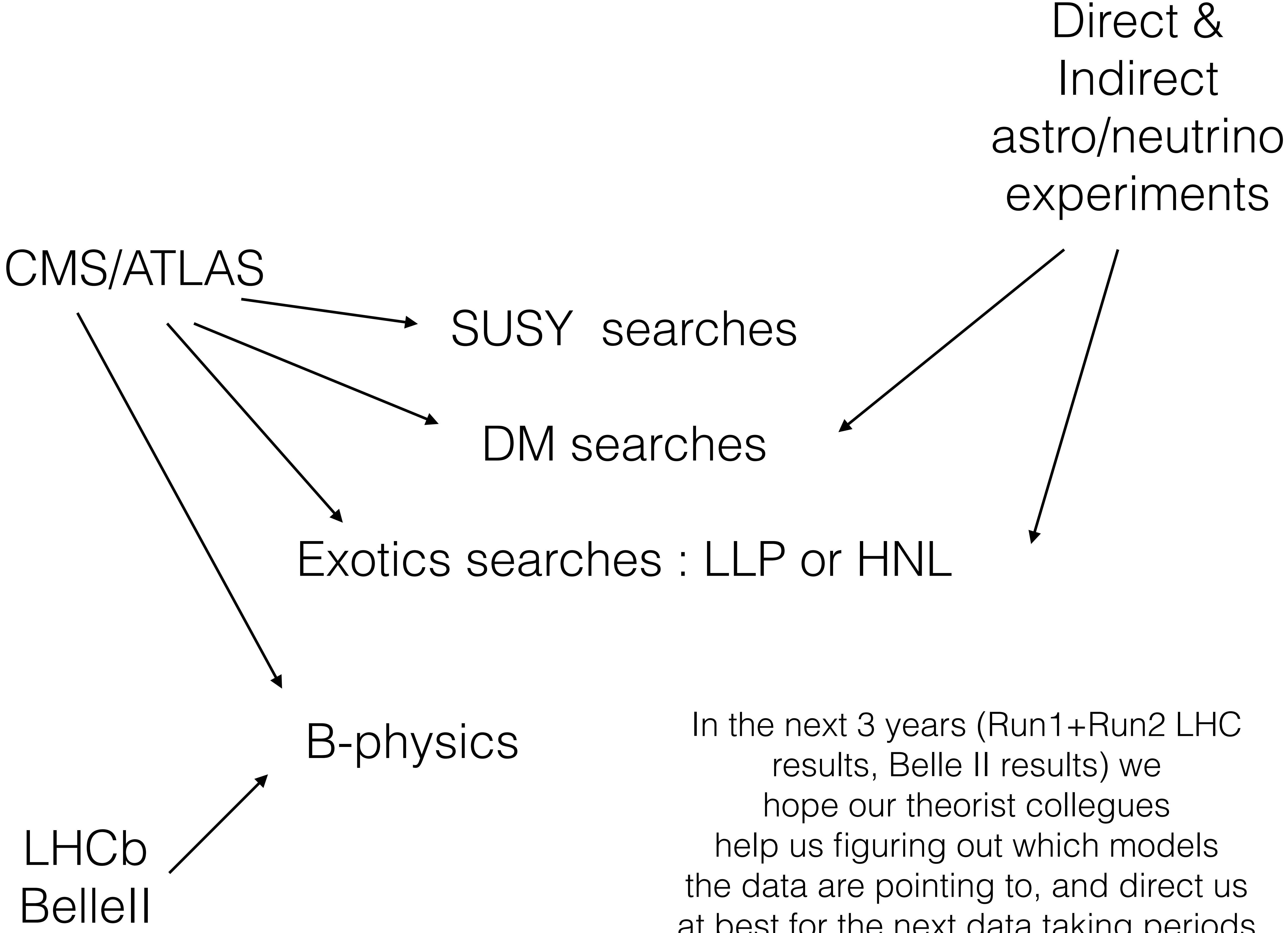
    - so high precision and high statistics and smart analysis methods are needed to catch an indirect glimpse at the new scale

SUSY searches

DM searches

Exotics searches : LLP or HNL

B-physics



Direct &
Indirect
astro/neutrino
experiments

CMS/ATLAS

SUSY searches

DM searches

Exotics searches : LLP or HNL

B-physics

LHCb
BelleII

In the next 3 years (Run1+Run2 LHC results, Belle II results) we hope our theorist collegues help us figuring out which models the data are pointing to, and direct us at best for the next data taking periods https://arxiv.org/pdf/1806.11484.pdf

Cleverly looking at the data

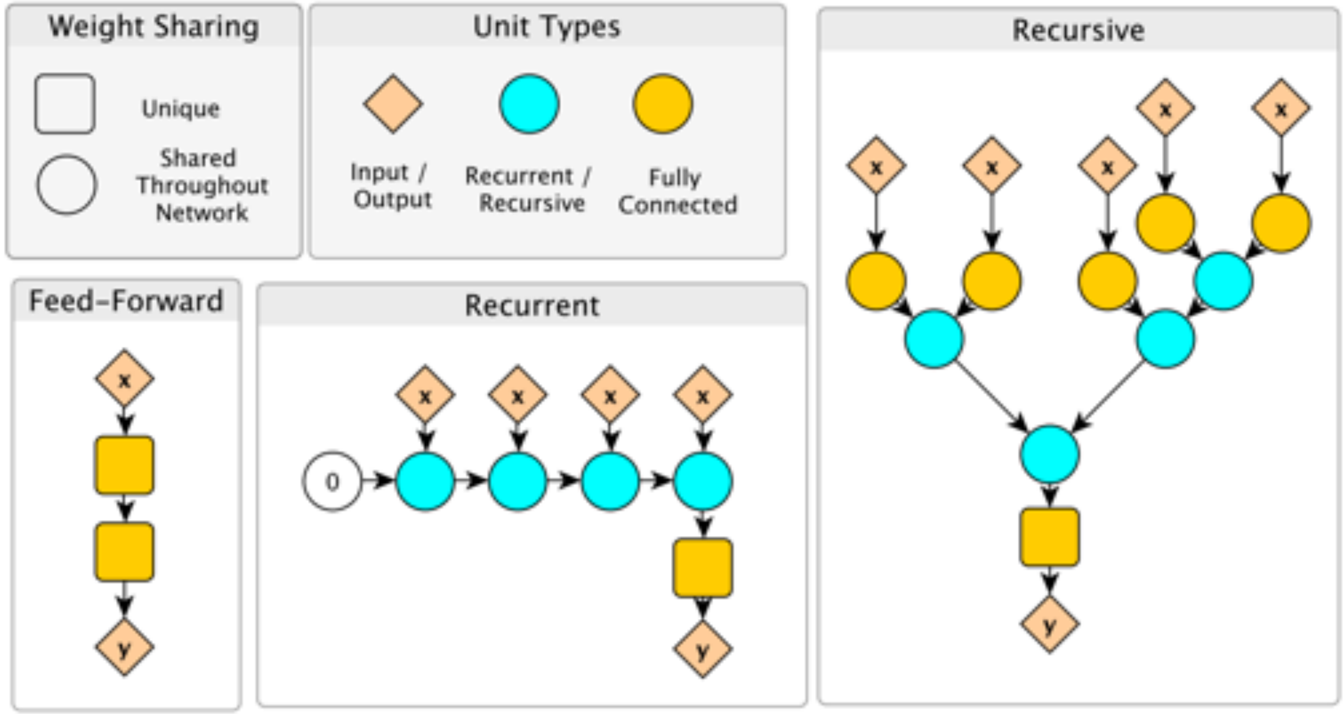
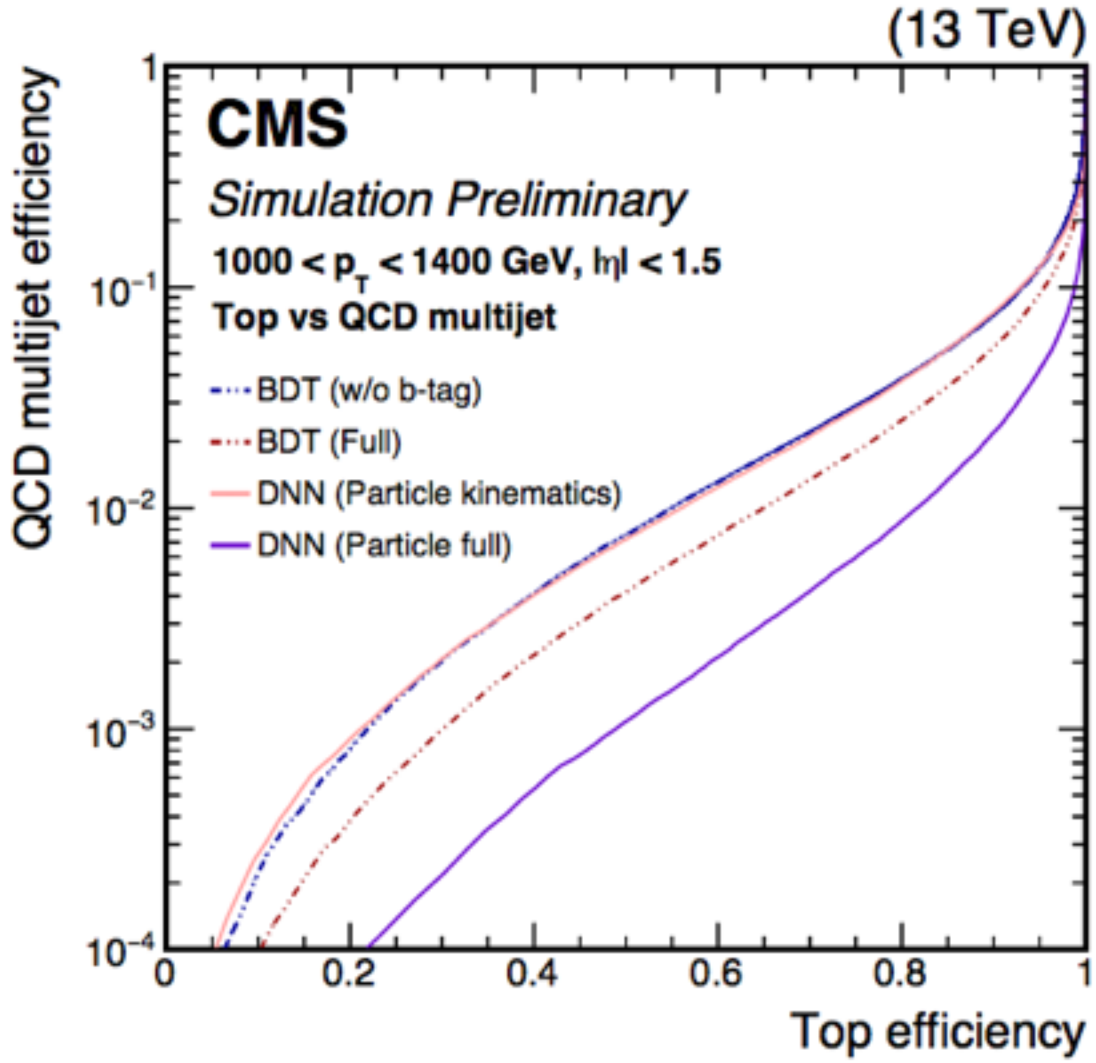


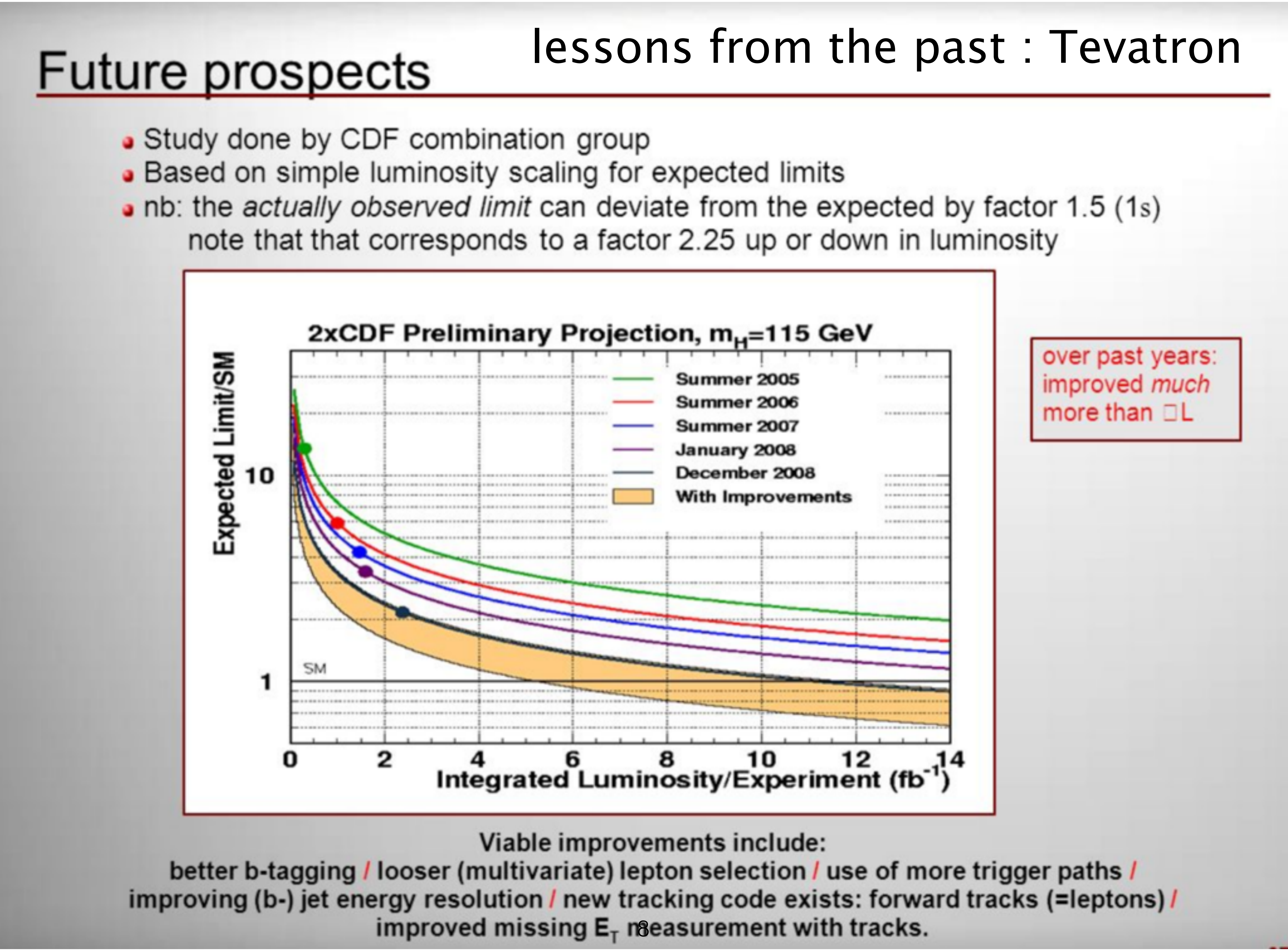
Figure 1

Schematic showing feed-forward, recurrent, and recursive neural network architectures. Diamonds represent inputs and outputs, while processing units are represented with circles and squares. Arrows between processing units represent embeddings $\boldsymbol{h}$. Standard feed-forward networks map a fixed length $\boldsymbol{x}$ into $\boldsymbol{y}$, whereas recurrent and recursive networks can process a sequence of inputs $\{\boldsymbol{x}_i\}$. Units represented as circles are shared throughout the network: once the network is trained, the units can be used to build a network of arbitrary size. Recurrent networks can be viewed as a subset of recursive networks, in which each node combines one input $\boldsymbol{x}_i$ and the output from the previous recurrent node $\boldsymbol{h}_{i-1}$ to produce $\boldsymbol{h}_i$, and where $\boldsymbol{h}_0 = 0$. Recursive units map each pair of inputs to an output in the same space, $(\boldsymbol{h}_i, \boldsymbol{h}_j) \rightarrow \boldsymbol{h}_k$. Note that these components can also be chained: Any output node can also serve as an input node to another component.



machine learning techniques applied to LHC data analysis
show promising big steps in performance in the coming year(s)

lessons from the past : Tevatron



Future prospects

- Study done by CDF combination group
- Based on simple luminosity scaling for expected limits
- nb: the *actually observed limit* can deviate from the expected by factor 1.5 (1s)
  note that that corresponds to a factor 2.25 up or down in luminosity

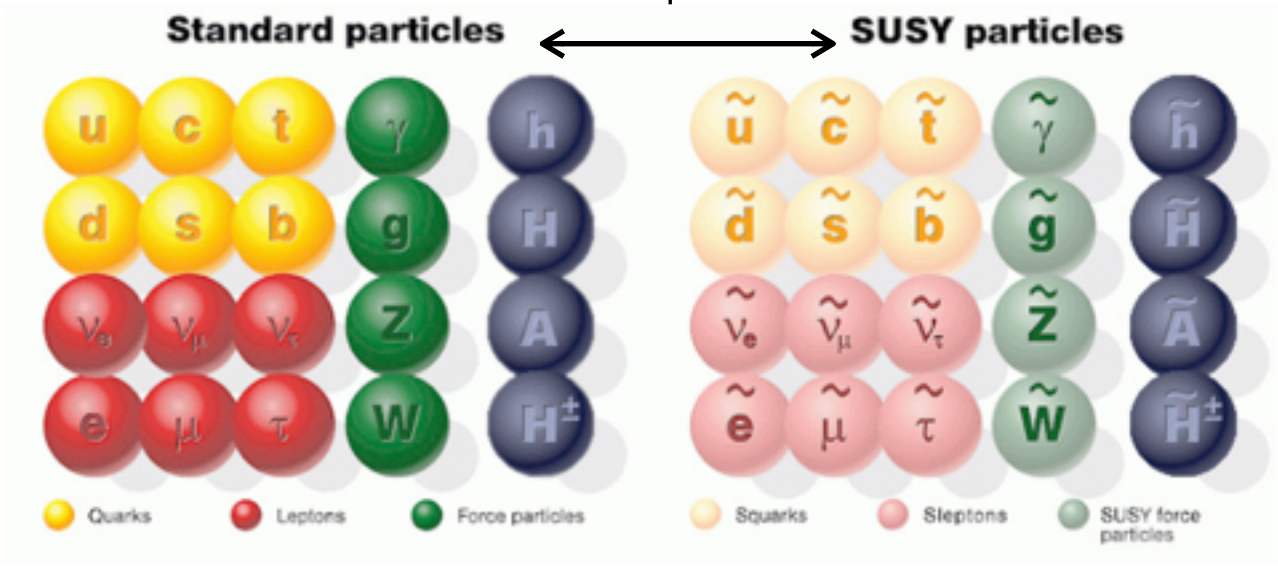
over past years: improved *much* more than □L

Viable improvements include:
better b-tagging / looser (multivariate) lepton selection / use of more trigger paths / improving (b-) jet energy resolution / new tracking code exists: forward tracks (=leptons) / improved missing E_T measurement with tracks.

- SUSY searches

Minimal Supersymmetric Standard Model

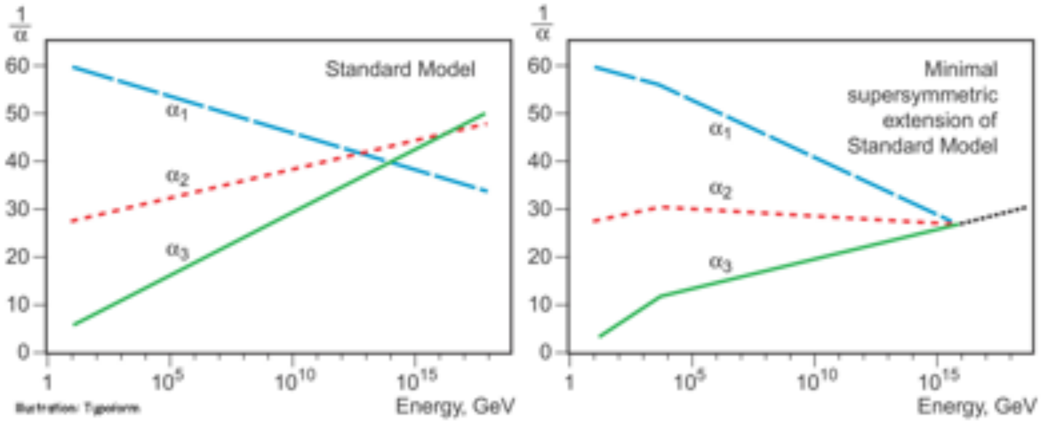
spin



$$P_R = (-1)^{3B+L+2s},$$

supersymmetry not broken = particle and sparticle have same mass and internal quantum numbers, except spin

supersymmetry spontaneously broken = particle and sparticle have different masses, sparticles are heavy



force strength unifies
at high E (early universe)

\+ new stable particle (if R parity conserved) :
neutralino:
a combination of higgsino, Wino, Bino
-> could be dark matter particle

\+ adds new particles that protect the higgs mass value from quantum corrections (new physics at ~ TeV scale)

Minimal Supersymmetric Standard Model

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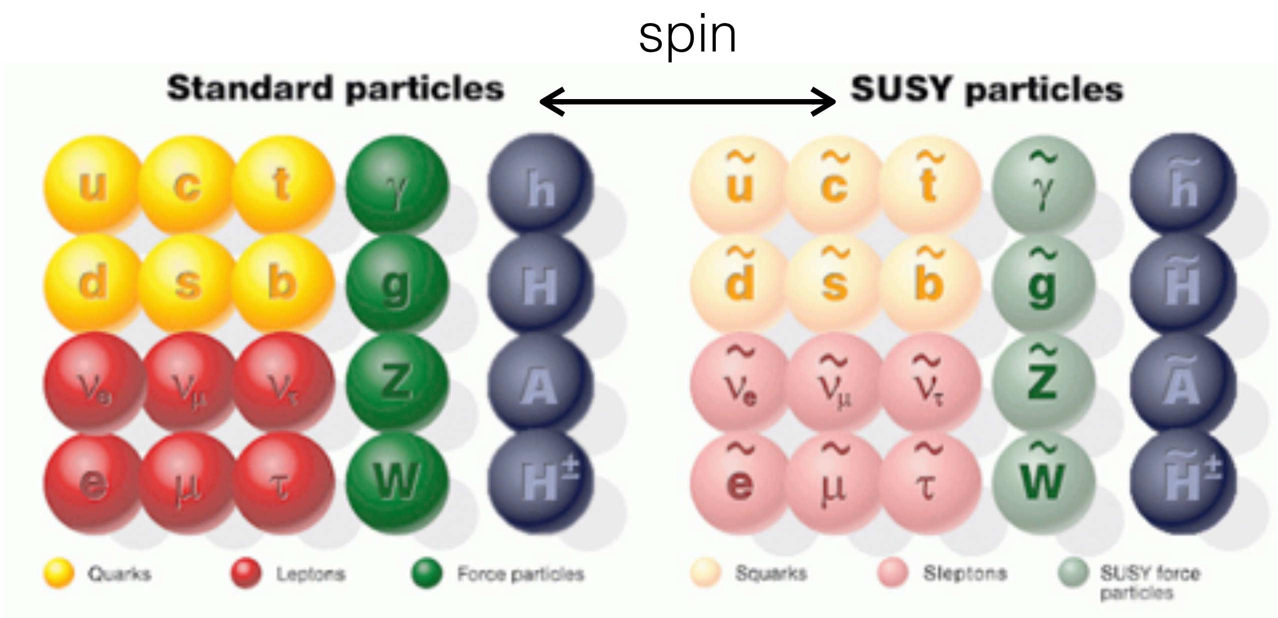

Problem:
more than
100 free
parameters !

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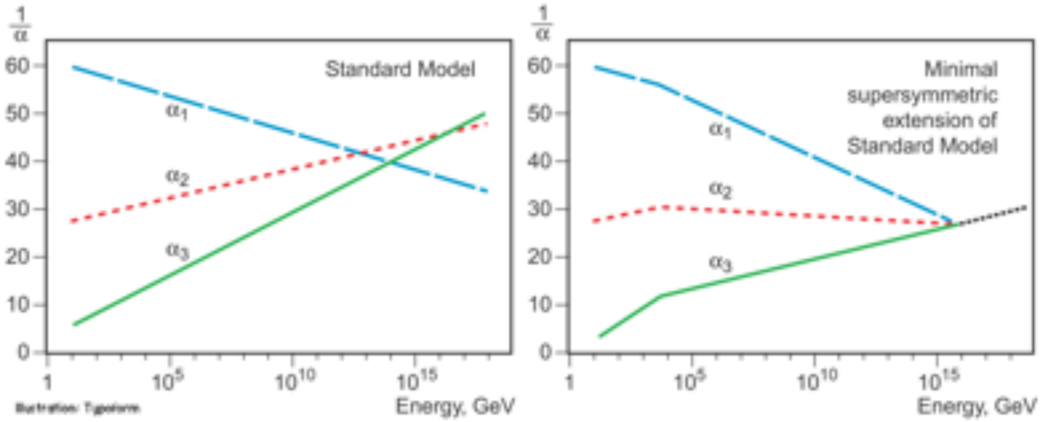

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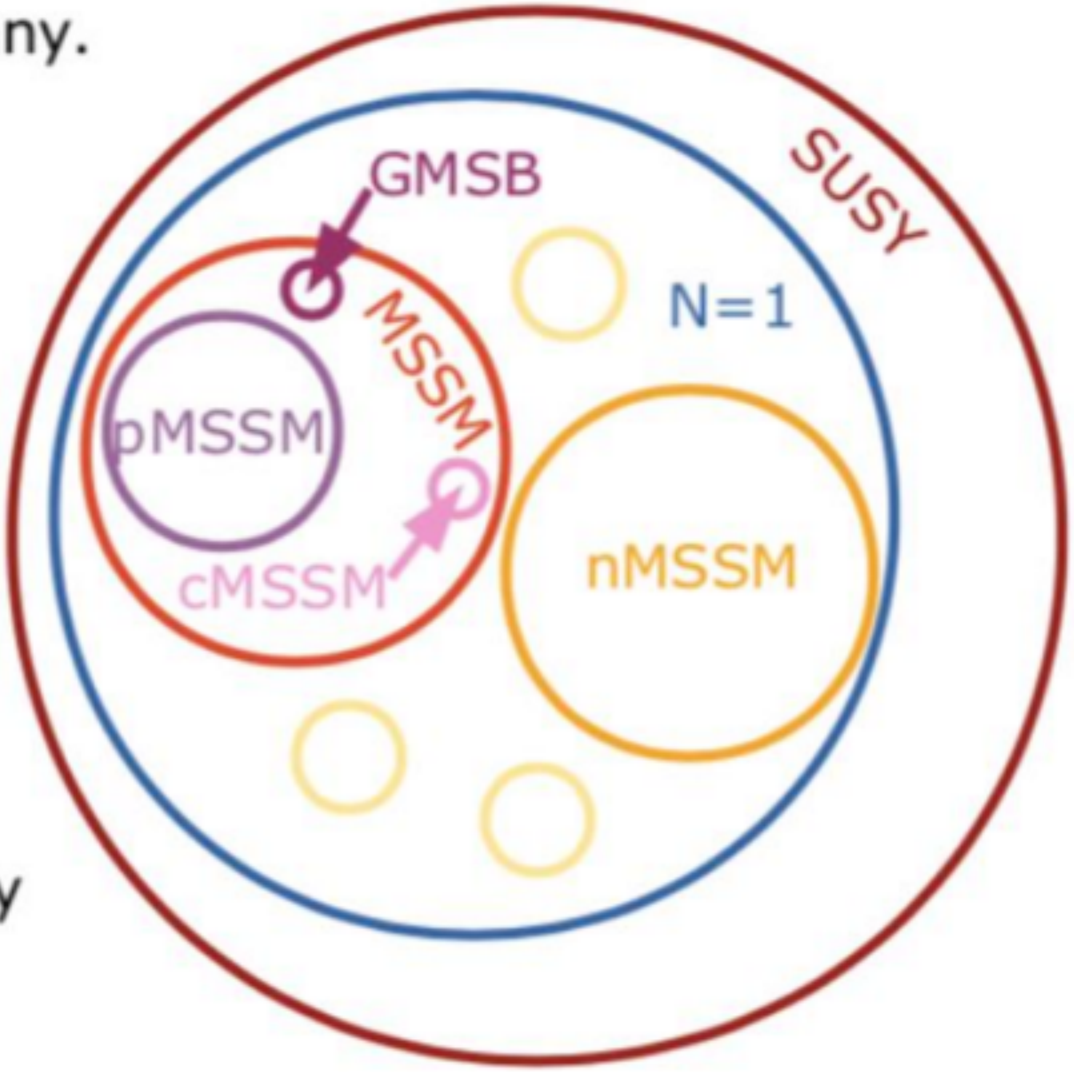
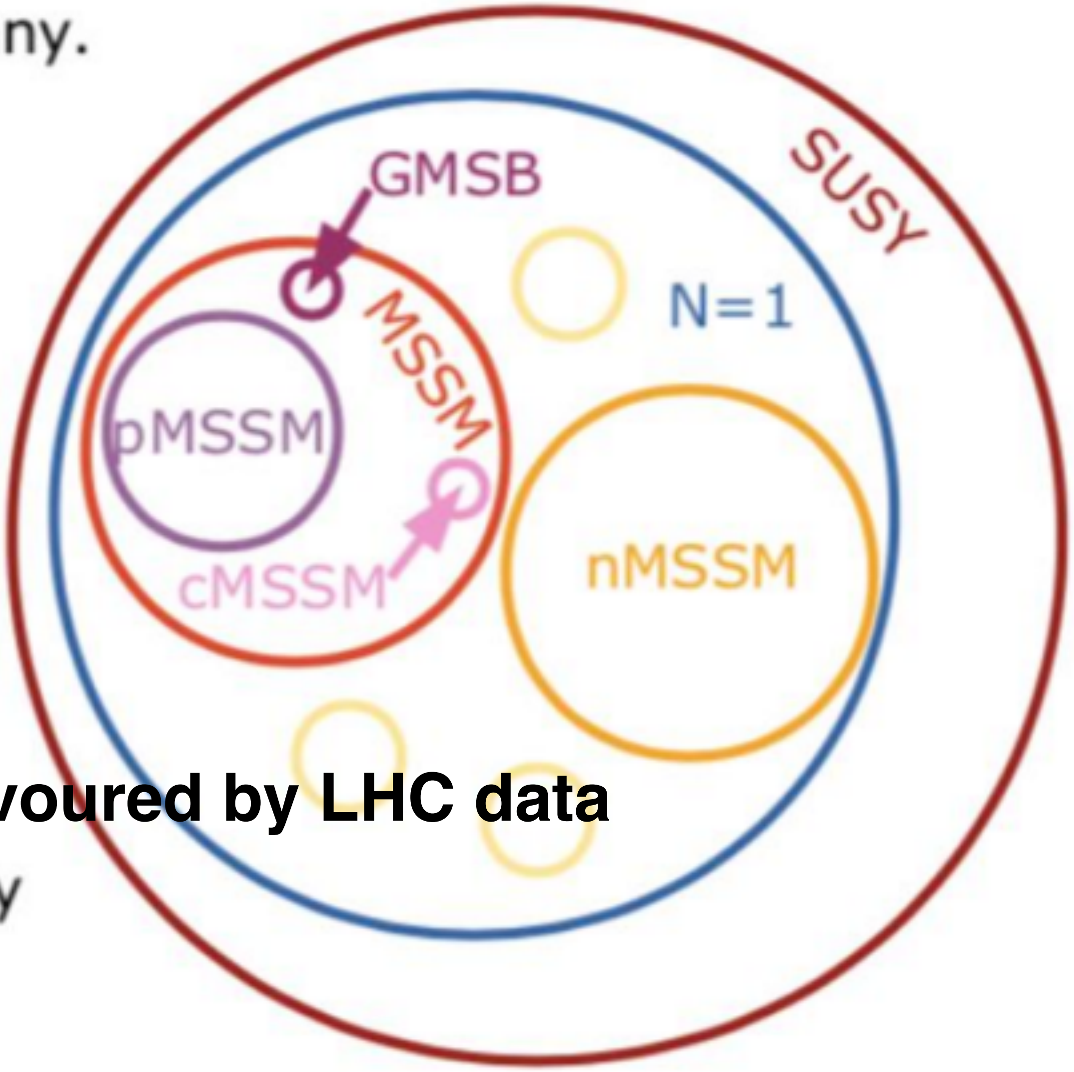


- SUSY is not one model, rather infinitely many.
- MSSM
  - Minimal new particle content.
  - No assumption on SUSY breaking → 120 additional free parameters.
- pMSSM
  - Reduce MSSM to 19 free parameters by imposing phenomenological and experimental constrains.
- cMSSM
  - Reduce MSSM to 5 free parameters by assuming universality at GUT scale.
- GMSB/AMSB
  - Reduce MSSM to 5 free parameters by assuming SUSY breaking mechanism.
- NMSSM
  - Extend MSSM by adding an additional singlet chiral superfield.
- Simplified Models
  - Masses of non-relevant SUSY particles are put very large.
  - 100% BR to single final state.

From «SUSY Searches at ATLAS and CMS» - Marija Vranjes Milosavljevic - PPC 2018



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- pMSSM
  - Reduce MSSM to 19 free parameters by imposing phenomenological and experimental constrains.
- ~~cMSSM~~ **simplest version, largely disfavoured by LHC data**
  - ~~Reduce MSSM to 5 free parameters by assuming universality at GUT scale.~~
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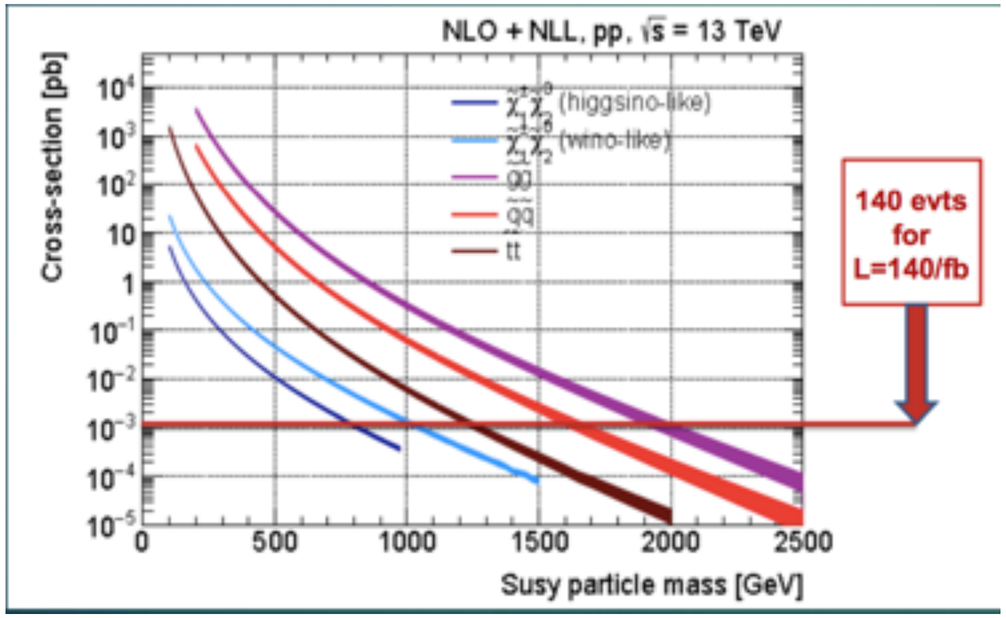
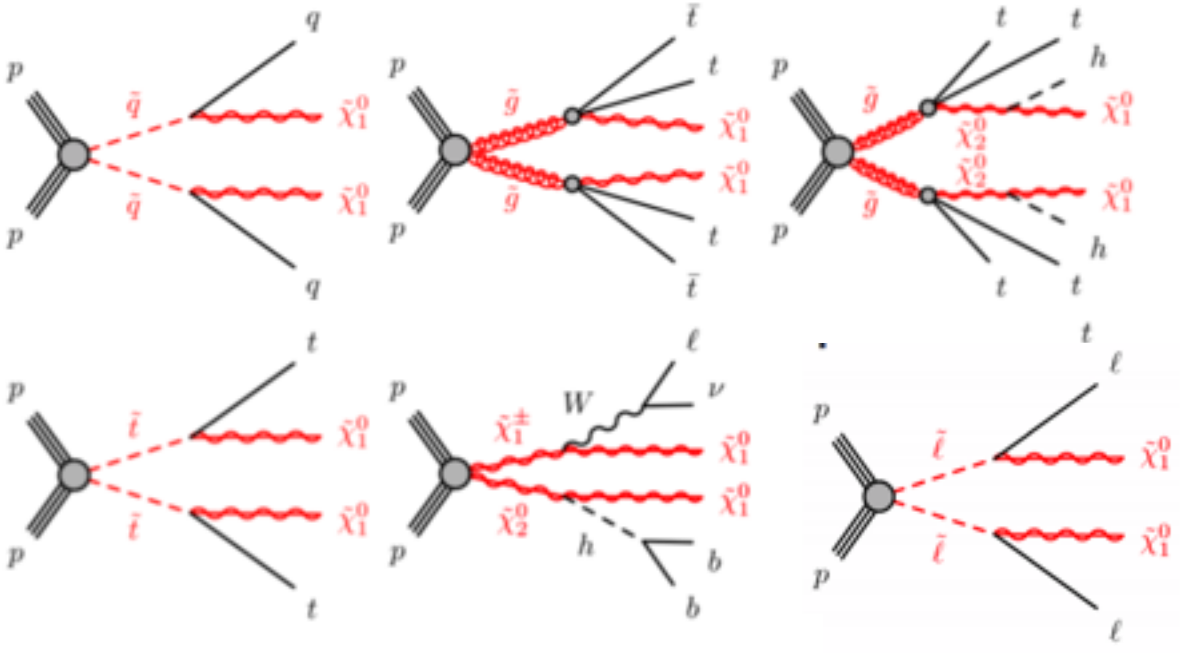
SUSY searching

Different kinds of sparticles are searched at the LHC

- Strong production (gluinos & 1st / 2nd generation squarks)
- Stop/sbottom production (3rd generation squarks)
- Electroweak production (gauginos & sleptons)



increase in energy really
helps SUSY searches. strong motivation for
plans for next colliders



Searches tested & optimised in the context of simplified models

Simplified models used for model-dependent exclusion limits.

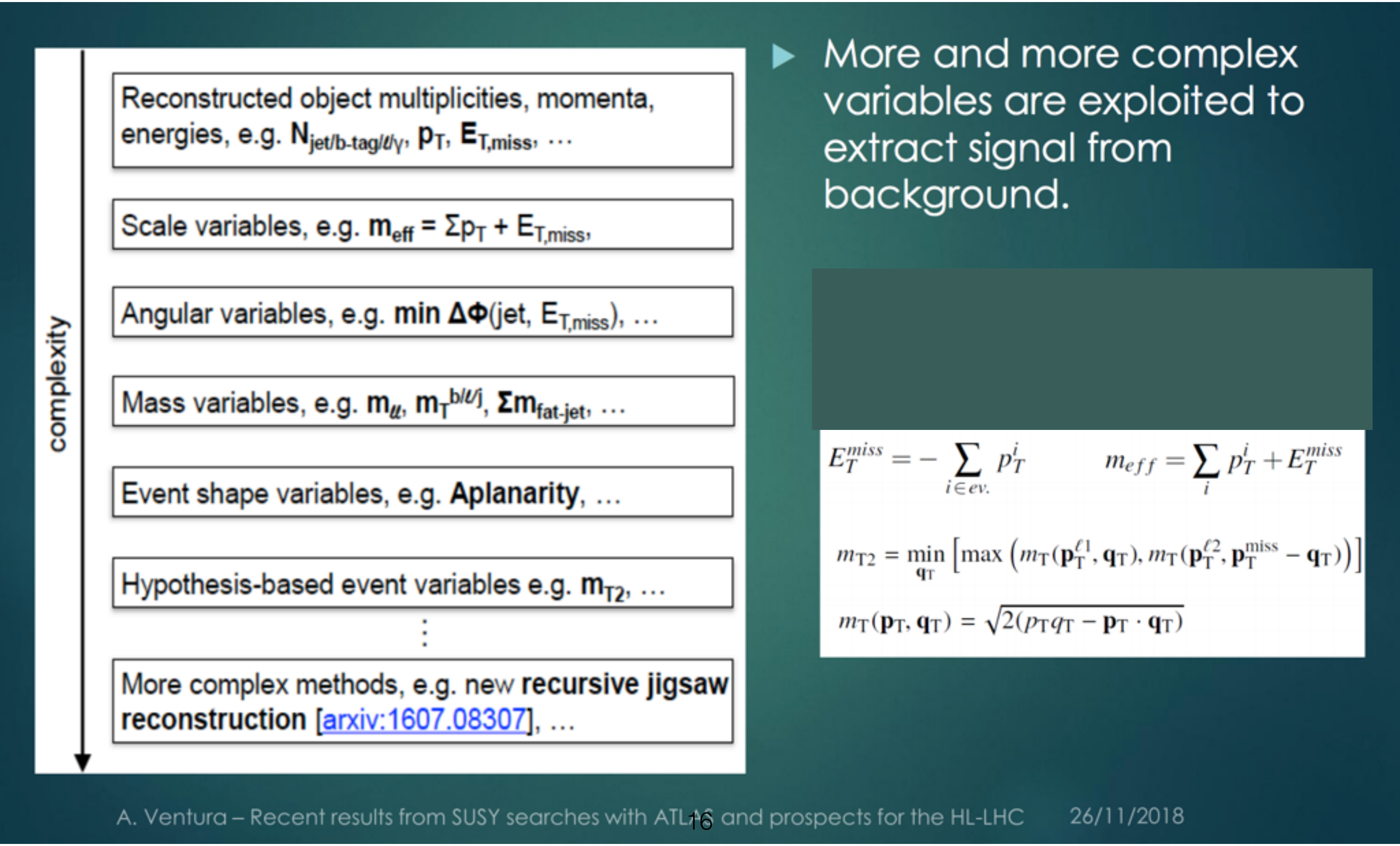
Model-independent upper limits, HEP data, for additional interpretations

SUSY search strategy

Different expected final states —> different categories :

— Object multiplicity: usually a very large combination of leptons/jets/MET is requested => sensitive to production & decay mechanisms
— Fermions: light flavor / heavy flavor final state quarks and leptons => sensitive to couplings
— Decays: displaced vertices, kinked particle tracks.

SUSY variables



Reconstructed object multiplicities, momenta, energies, e.g. $N_{jet/b\text{-}tag/\ell/\gamma}$, p_T, $E_{T,miss}$, …

Scale variables, e.g. $m_{eff} = \Sigma p_T + E_{T,miss}$,

Angular variables, e.g. **min ΔΦ**(jet, $E_{T,miss}$), …

Mass variables, e.g. $m_{\ell\ell}$, $m_T^{b/\ell/j}$, $\Sigma m_{fat\text{-}jet}$, …

Event shape variables, e.g. **Aplanarity**, …

Hypothesis-based event variables e.g. m_{T2}, …

⋮

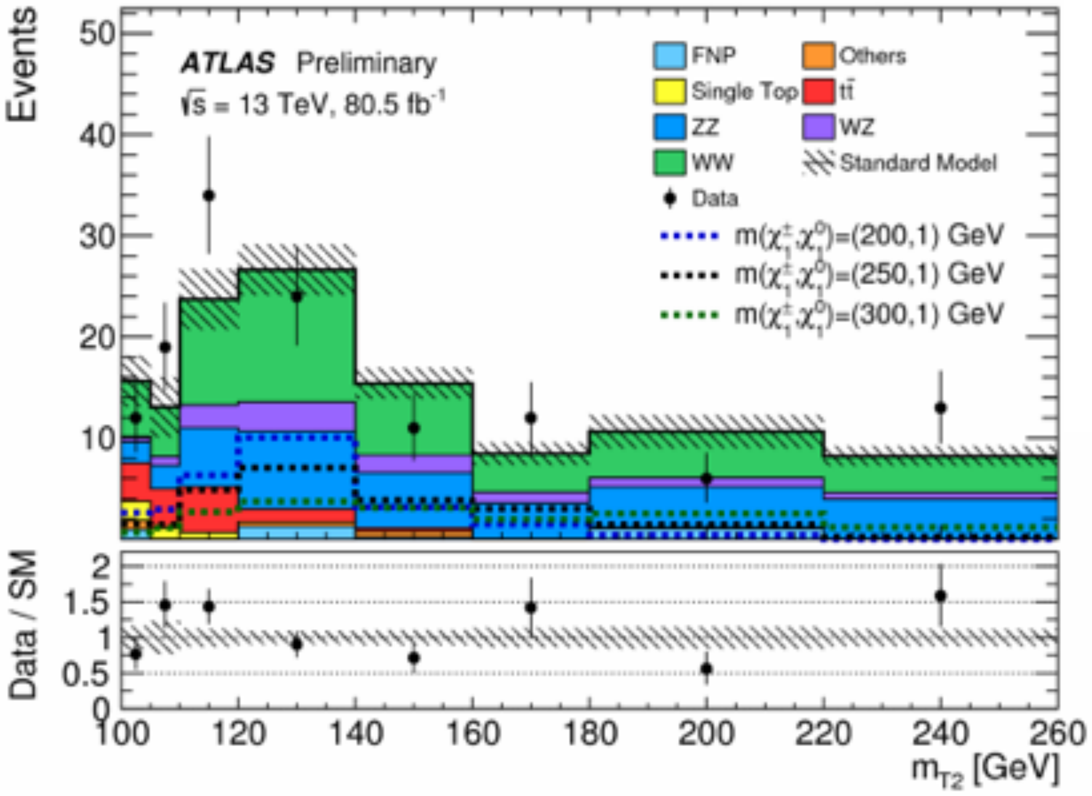
More complex methods, e.g. new **recursive jigsaw reconstruction** [arxiv:1607.08307], …

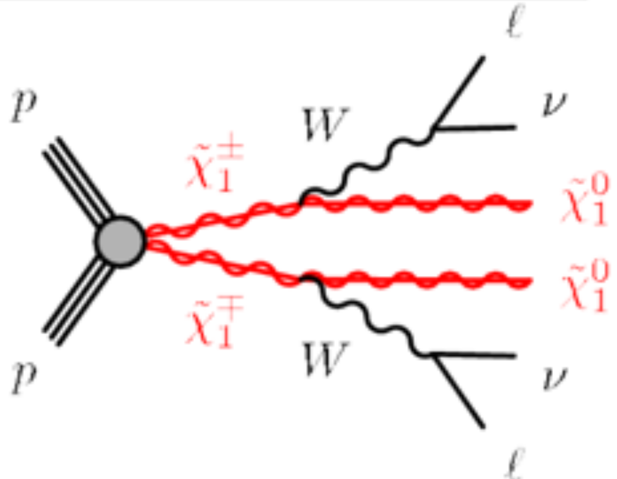
- More and more complex variables are exploited to extract signal from background.

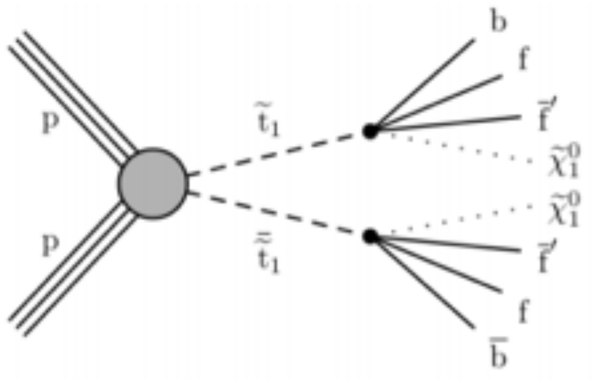
$$E_T^{miss} = -\sum_{i\in ev.} p_T^i \qquad m_{eff} = \sum_i p_T^i + E_T^{miss}$$

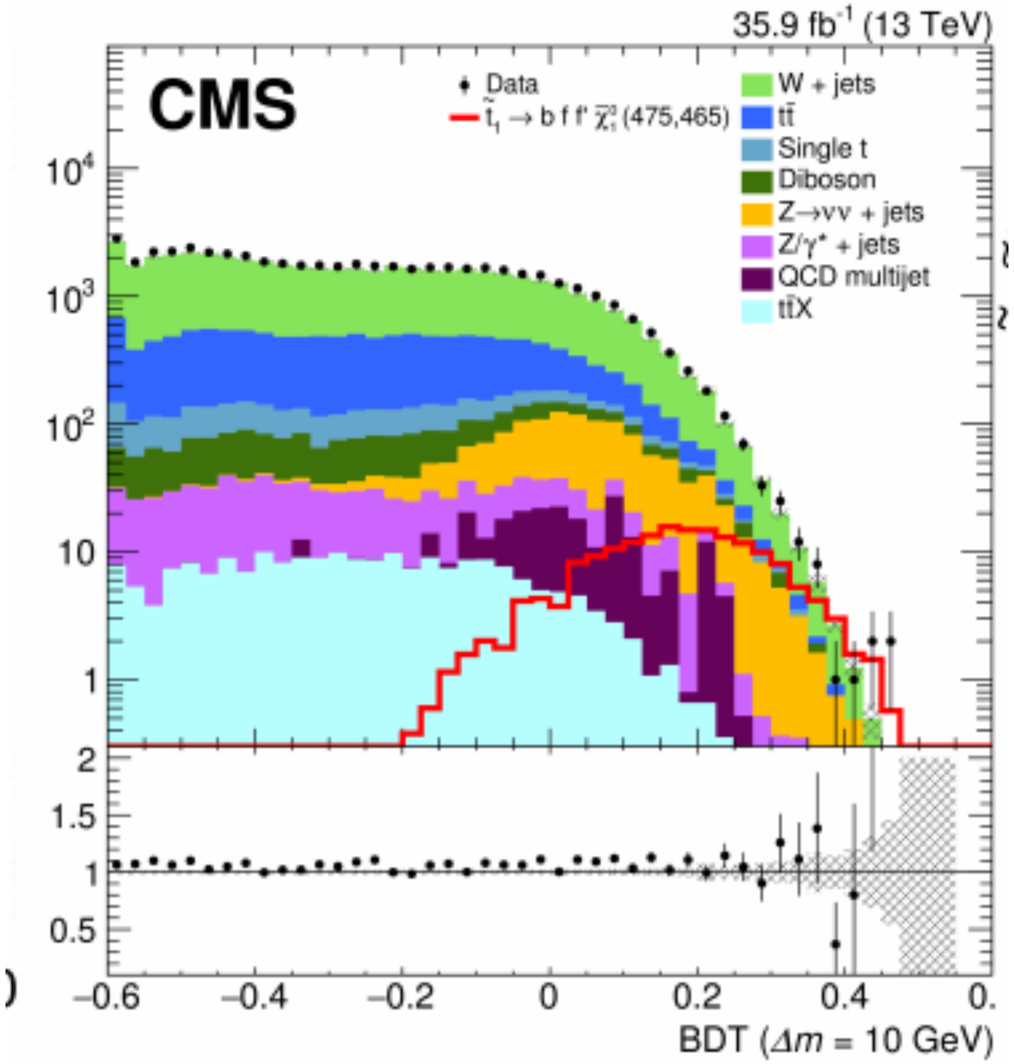
$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{miss} - \mathbf{q}_T)\right)\right]$$

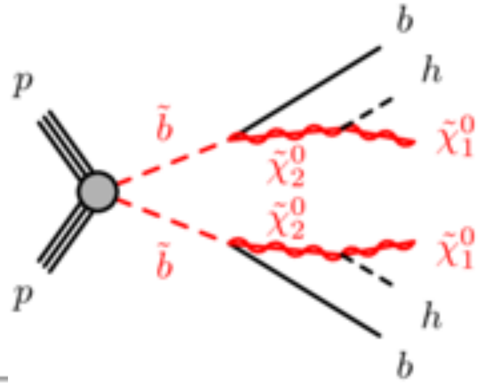
$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}$$

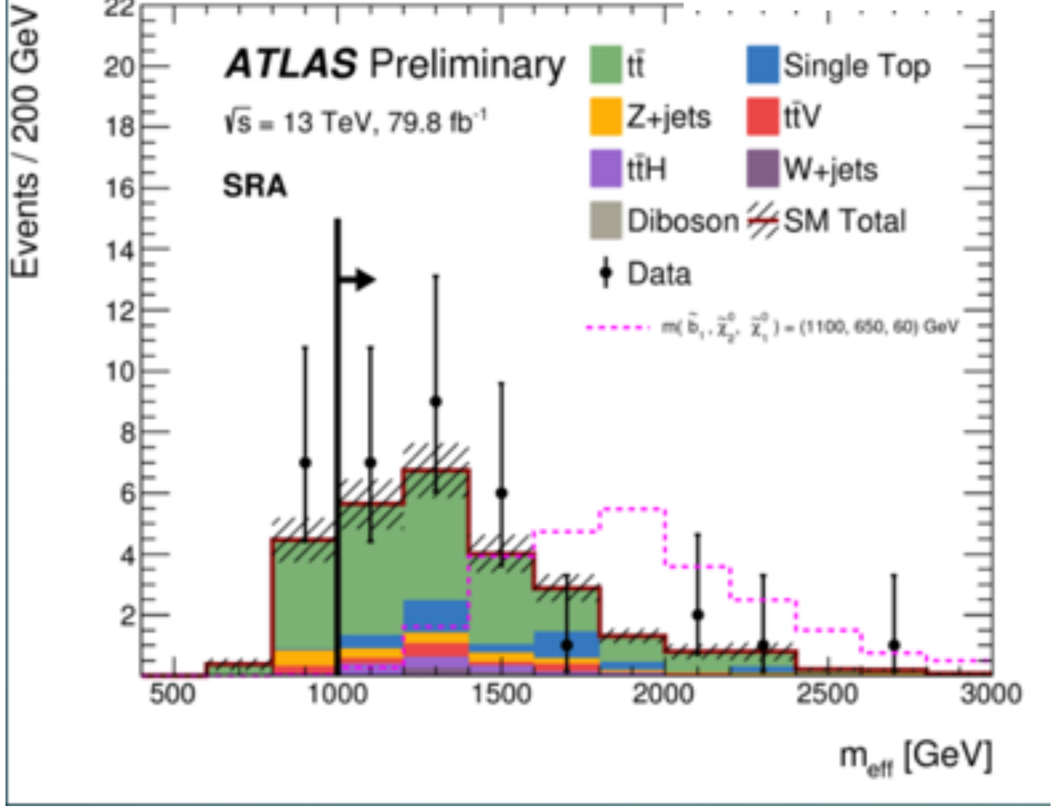

ATLAS Preliminary
√s = 13 TeV, 80.5 fb⁻¹
FNP
Others
Single Top
tt̄
ZZ
WZ
WW
Standard Model
Data
m(χ̃±1,χ̃01)=(200,1) GeV
m(χ̃±1,χ̃01)=(250,1) GeV
m(χ̃±1,χ̃01)=(300,1) GeV
Events
50
40
30
20
10
Data / SM
2
1.5
1
0.5
0
100
120
140
160
180
200
220
240
260
mT2 [GeV]


p
p
χ̃±1
χ̃∓1
W
W
ℓ
ν
χ̃01
χ̃01
ν
ℓ


p
p
t̃1
t̃1
b
f
f′
χ̃01
χ̃01
f′
f
b̄


35.9 fb⁻¹ (13 TeV)
CMS
Data
t̃1 → b f f′ χ̃01 (475,465)
W + jets
tt̄
Single t
Diboson
Z→νν + jets
Z/γ* + jets
QCD multijet
tt̄X
10⁴
10³
10²
10
1
2
1.5
1
0.5
−0.6
−0.4
−0.2
0
0.2
0.4
BDT (Δm = 10 GeV)


p
p
b̃
b̃
b
h
χ̃01
χ̃02
χ̃02
χ̃01
h
b


ATLAS Preliminary
√s = 13 TeV, 79.8 fb⁻¹
SRA
tt̄
Single Top
Z+jets
tt̄V
tt̄H
W+jets
Diboson
SM Total
Data
m(b̃1, χ̃02, χ̃01) = (1100, 650, 60) GeV
Events / 200 GeV
22
20
18
16
14
12
10
8
6
4
2
500
1000
1500
2000
2500
3000
meff [GeV]

SUSY search strategy

Different expected final states —> different categories :

— Object multiplicity: usually a very large combination of leptons/jets/MET is requested => sensitive to production & decay mechanisms
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Distinct features of SUSY processes
(determine the phase space)
— Missing energy: sensitive to the properties of the invisible states, e.g. how many neutralinos in the event, what is their mass, etc.
— Energy scale: m(eff) sensitive to the overall energy scale of the event, e.g. the mass of the gluino
— Energy structure: ΣM_J sensitive to the structure of the visible energy, e.g. how many partons are generated in decay, how energy is partitioned across the final state objects (both visible and invisible).
— Reference frame (Recursive jigsaw technique)

All these used in defining signal regions to search for SUSY!

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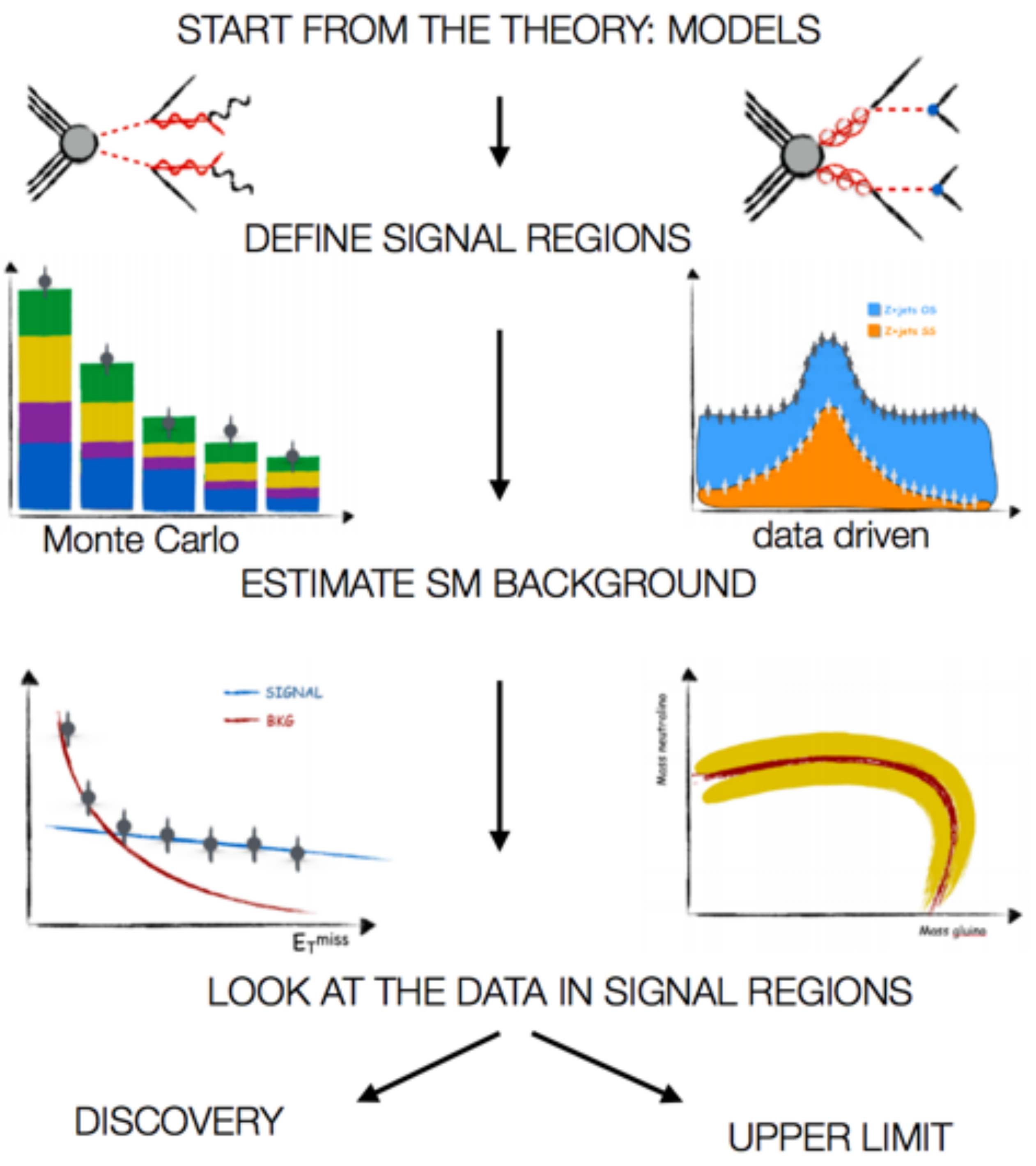


START FROM THE THEORY: MODELS

DEFINE SIGNAL REGIONS

Monte Carlo

data driven

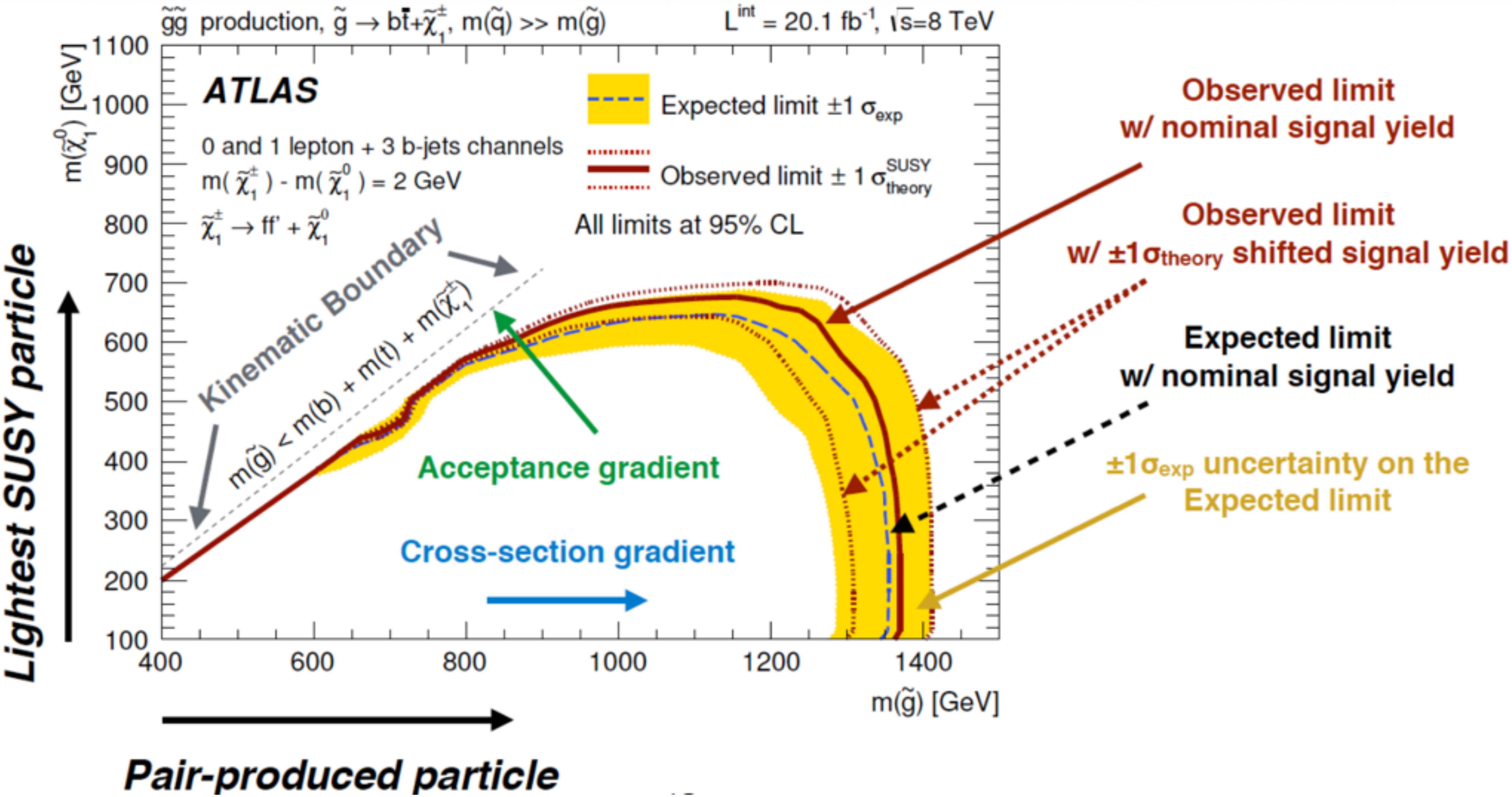
ESTIMATE SM BACKGROUND

LOOK AT THE DATA IN SIGNAL REGIONS

DISCOVERY

UPPER LIMIT

interpretation of SUSY results/plots



Acceptance gradient

Cross-section gradient

Observed limit w/ nominal signal yield

Observed limit w/ ±1σ$_{theory}$ shifted signal yield

Expected limit w/ nominal signal yield

±1σ$_{exp}$ uncertainty on the Expected limit

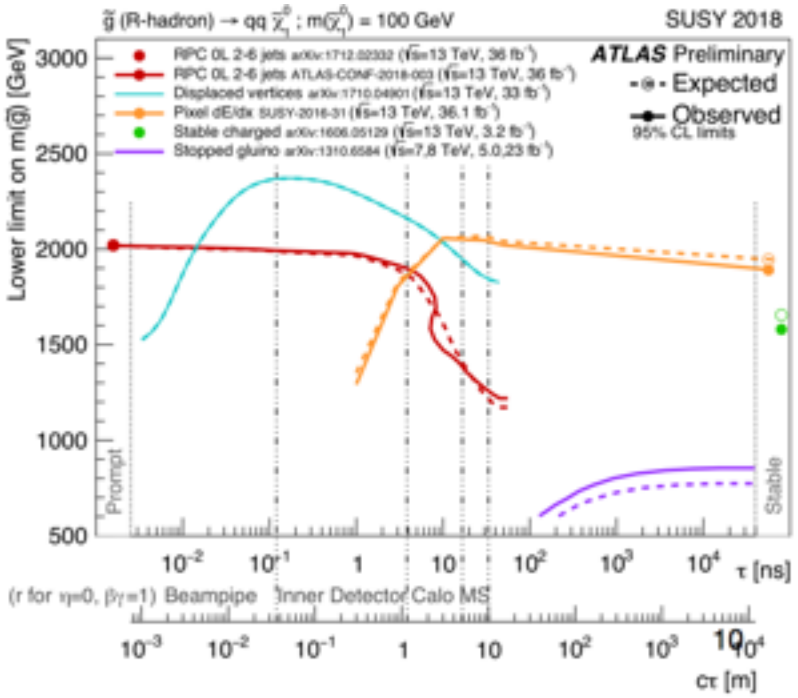
Lightest SUSY particle

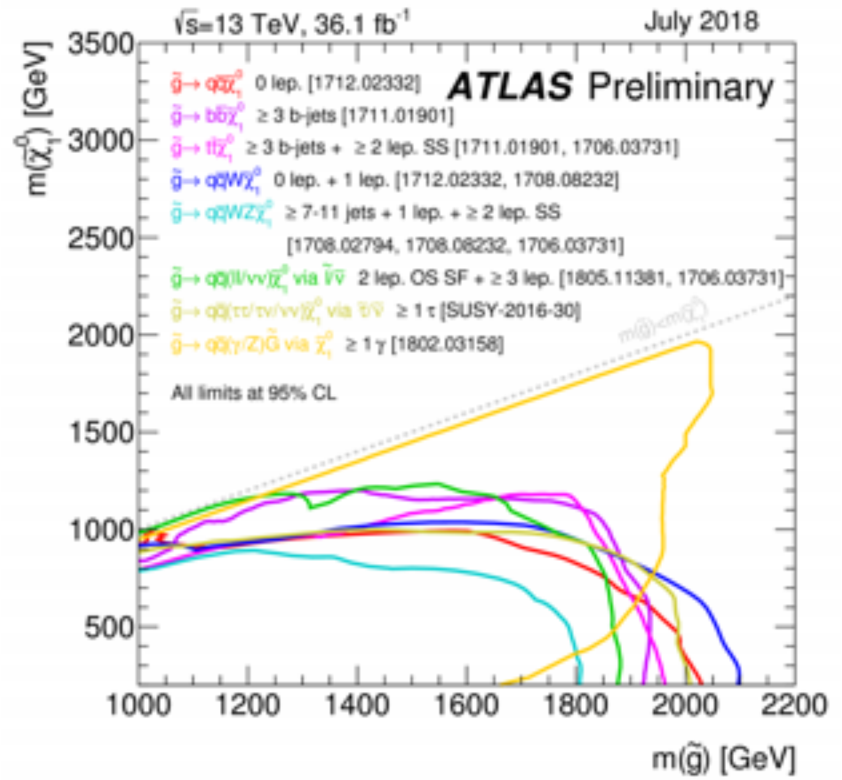
Pair-produced particle

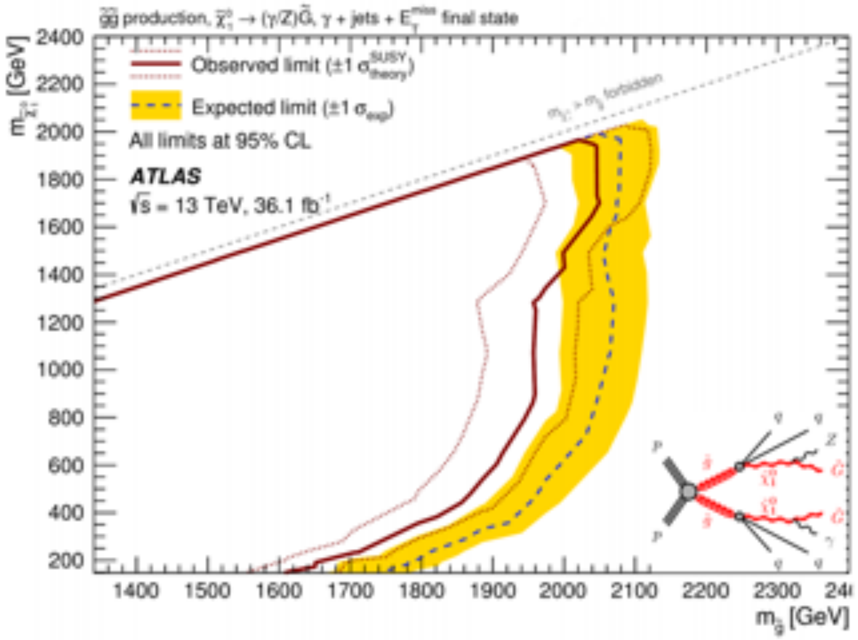
Strong production

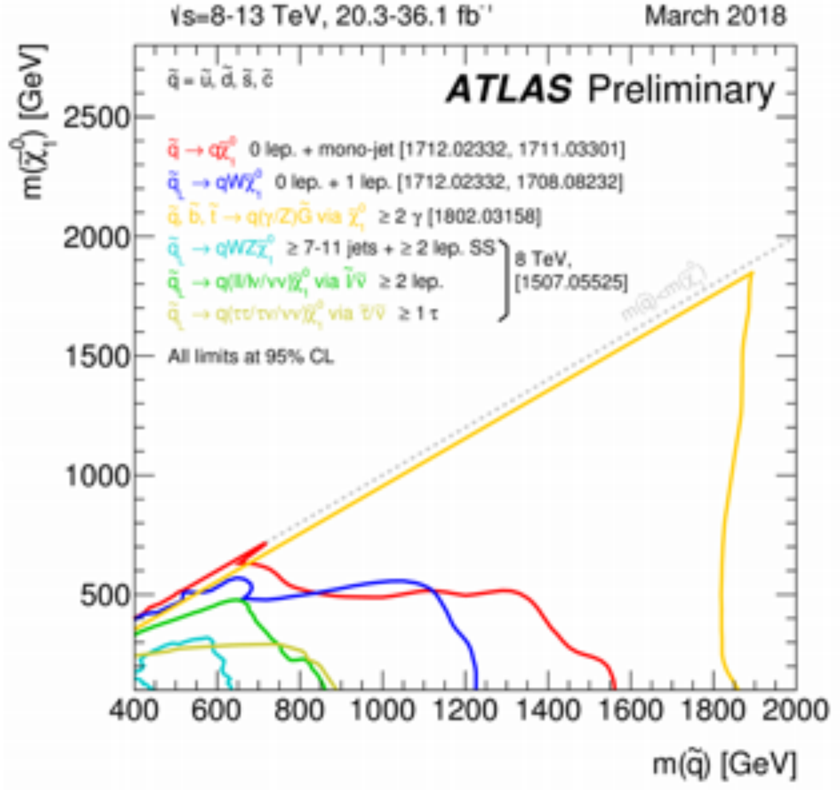
improvements in Run-2 :
- energy increase in LHC
- reconstruction and selection
- trigger (close gaps towards

limit m(χ)=m(sgluino)
- lifetime coverage

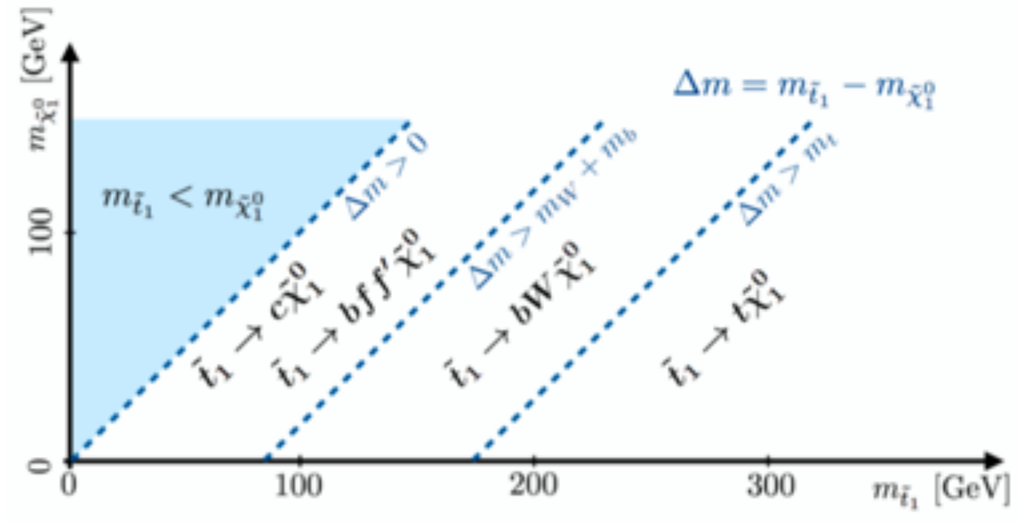






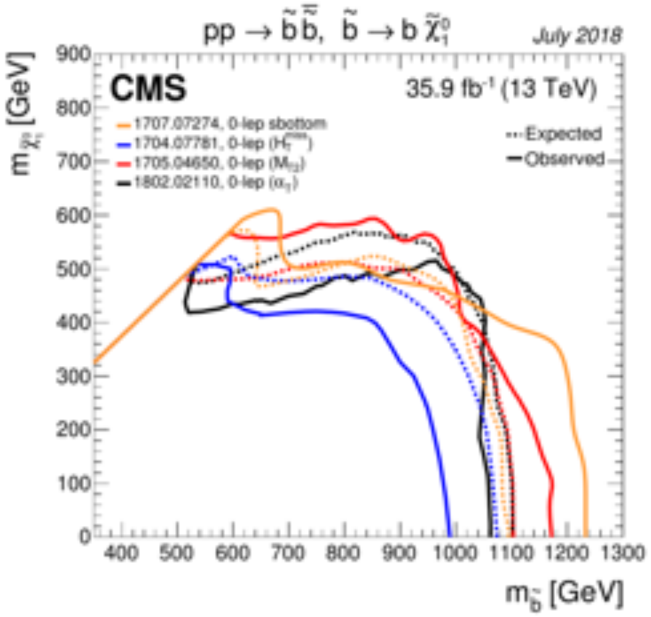


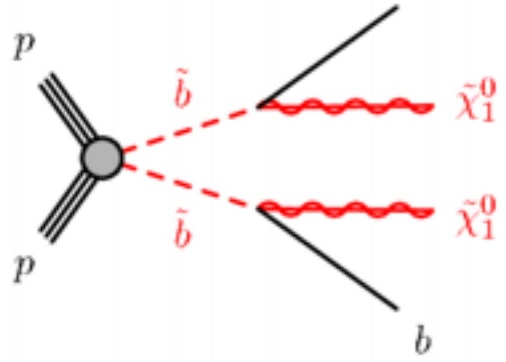
stop/sbottom production

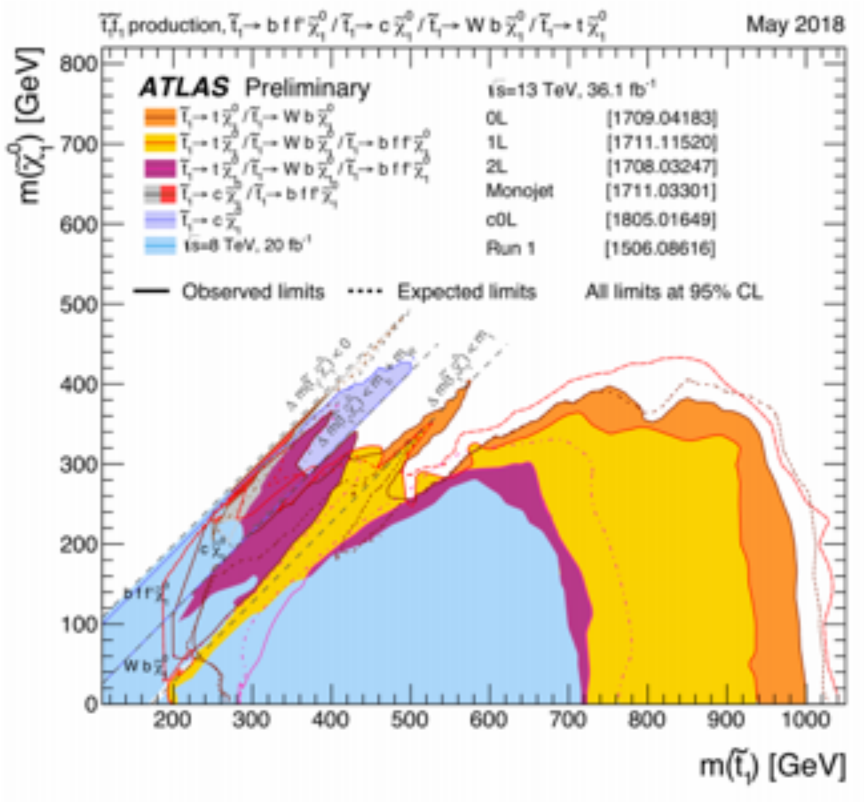


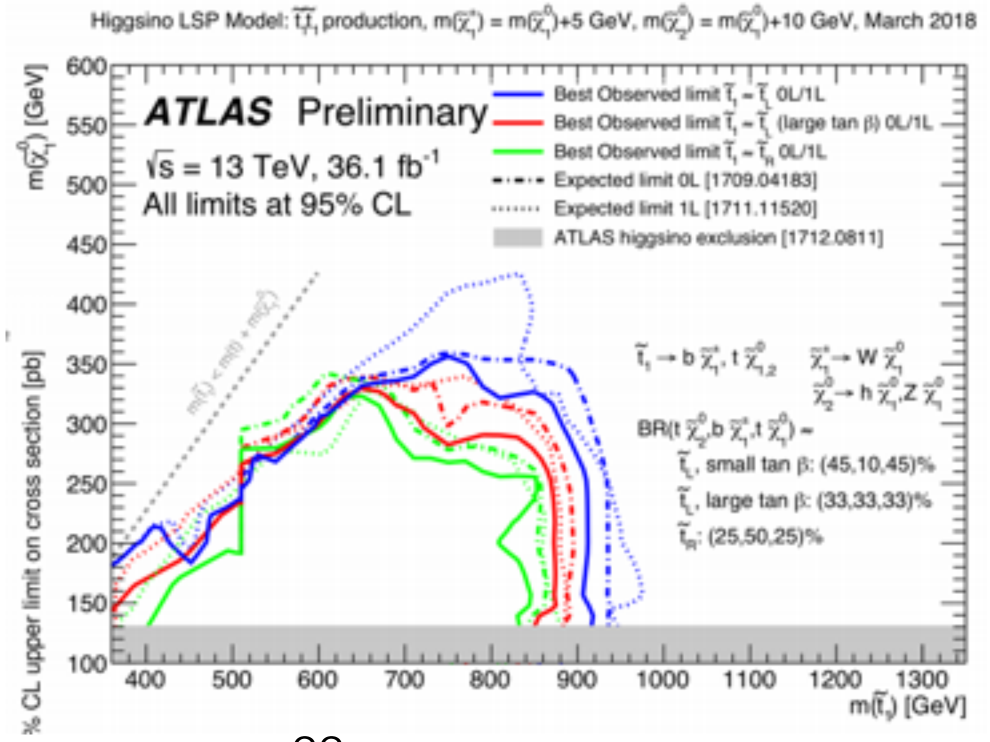
large E^{miss}_T
b-tagging
soft leptons
initial state radiation high-pT jet
in compressed scenarios

all penalize stats further ->
weaker limits



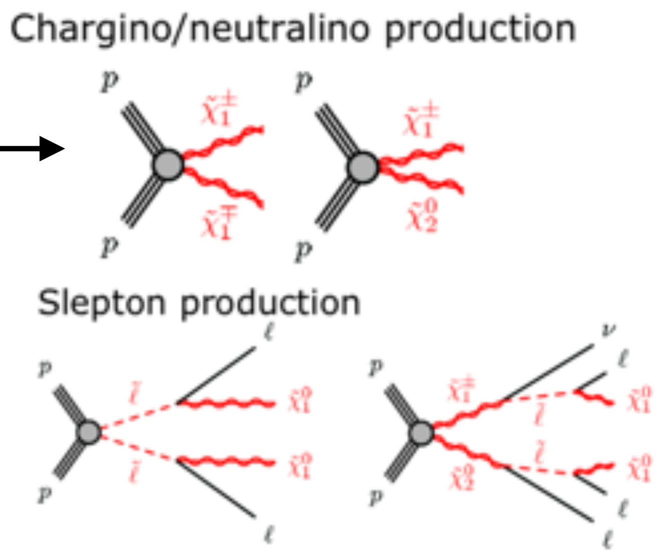


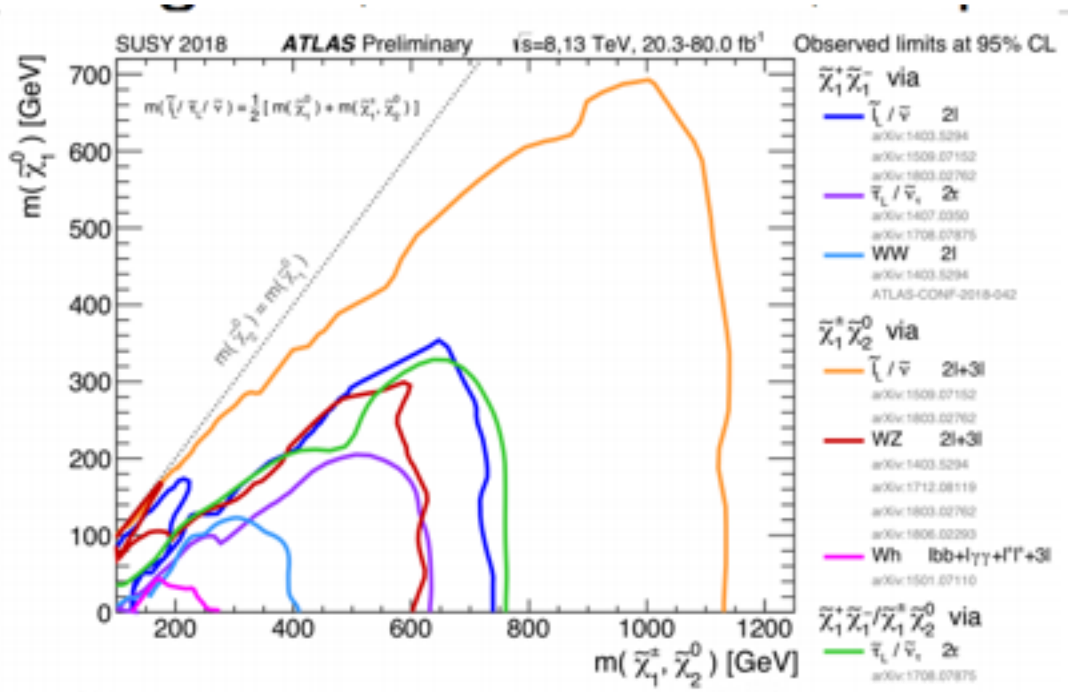


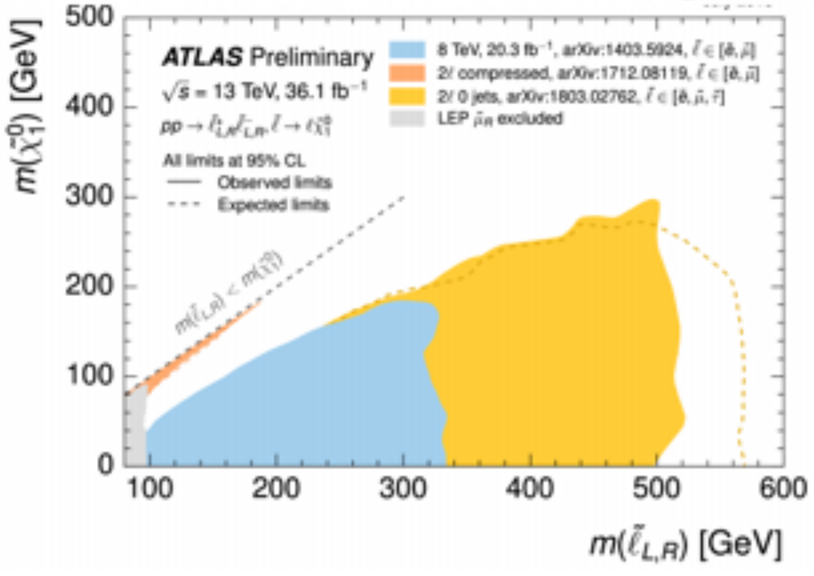


Electroweak production

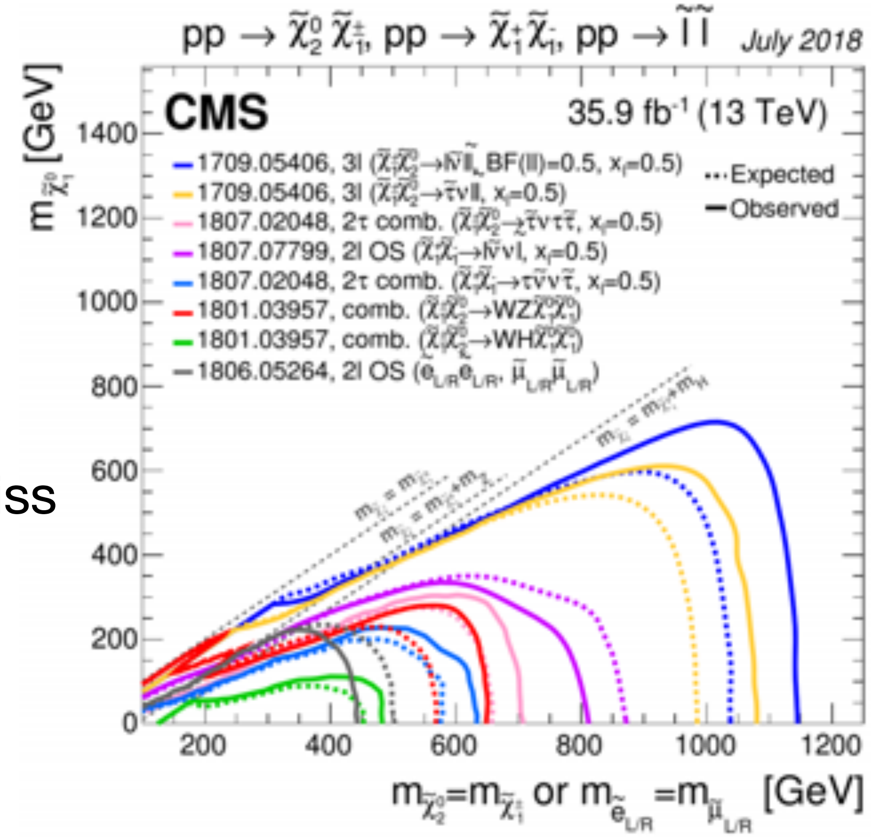
typically you would ask
large E^{miss}_T
or high-pT initial
state radiation jet →

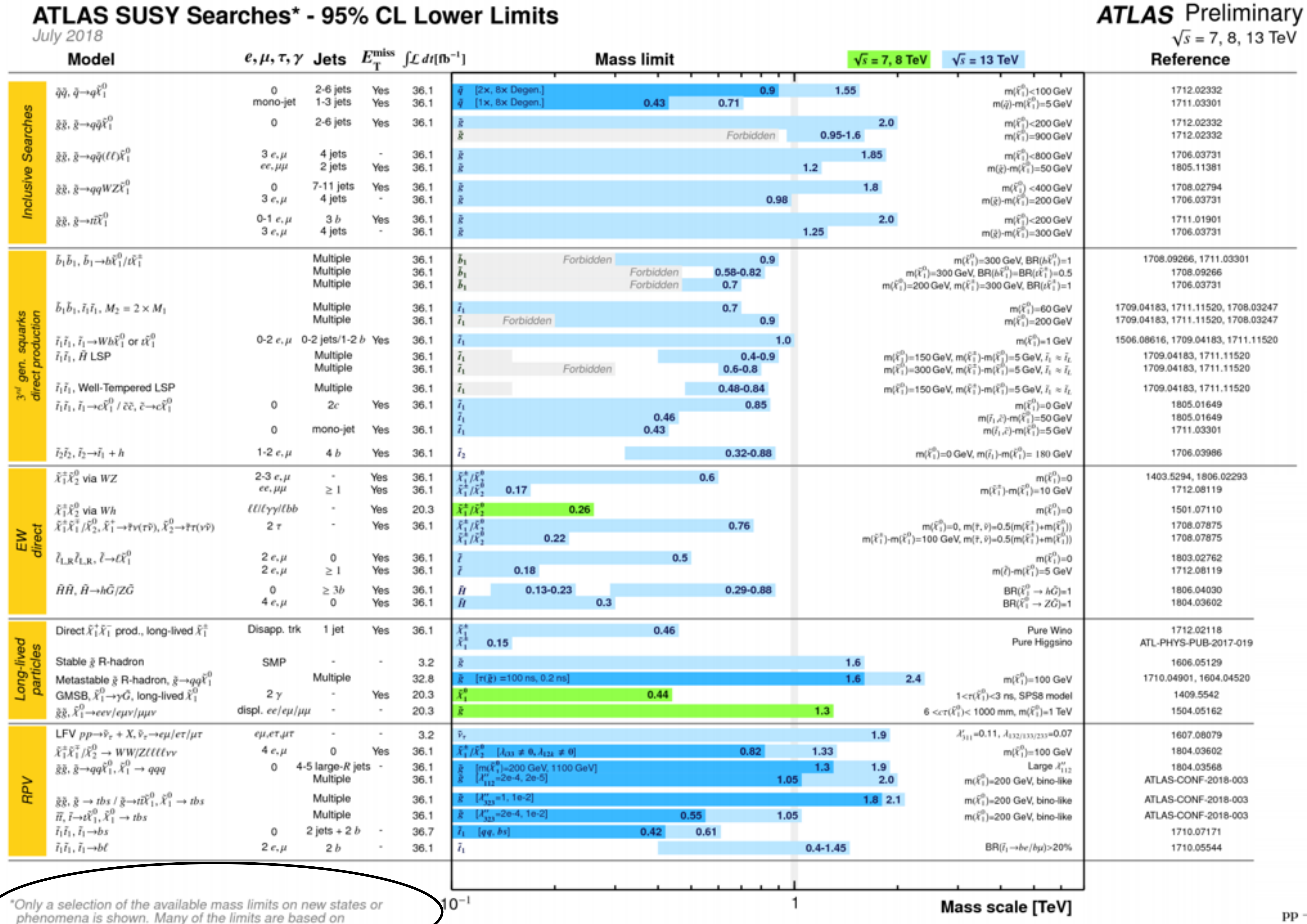






large E^{miss}_T
not many jets
Compressed scenarios:
soft leptons + ISR jets + EtMiss
low cross section





ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

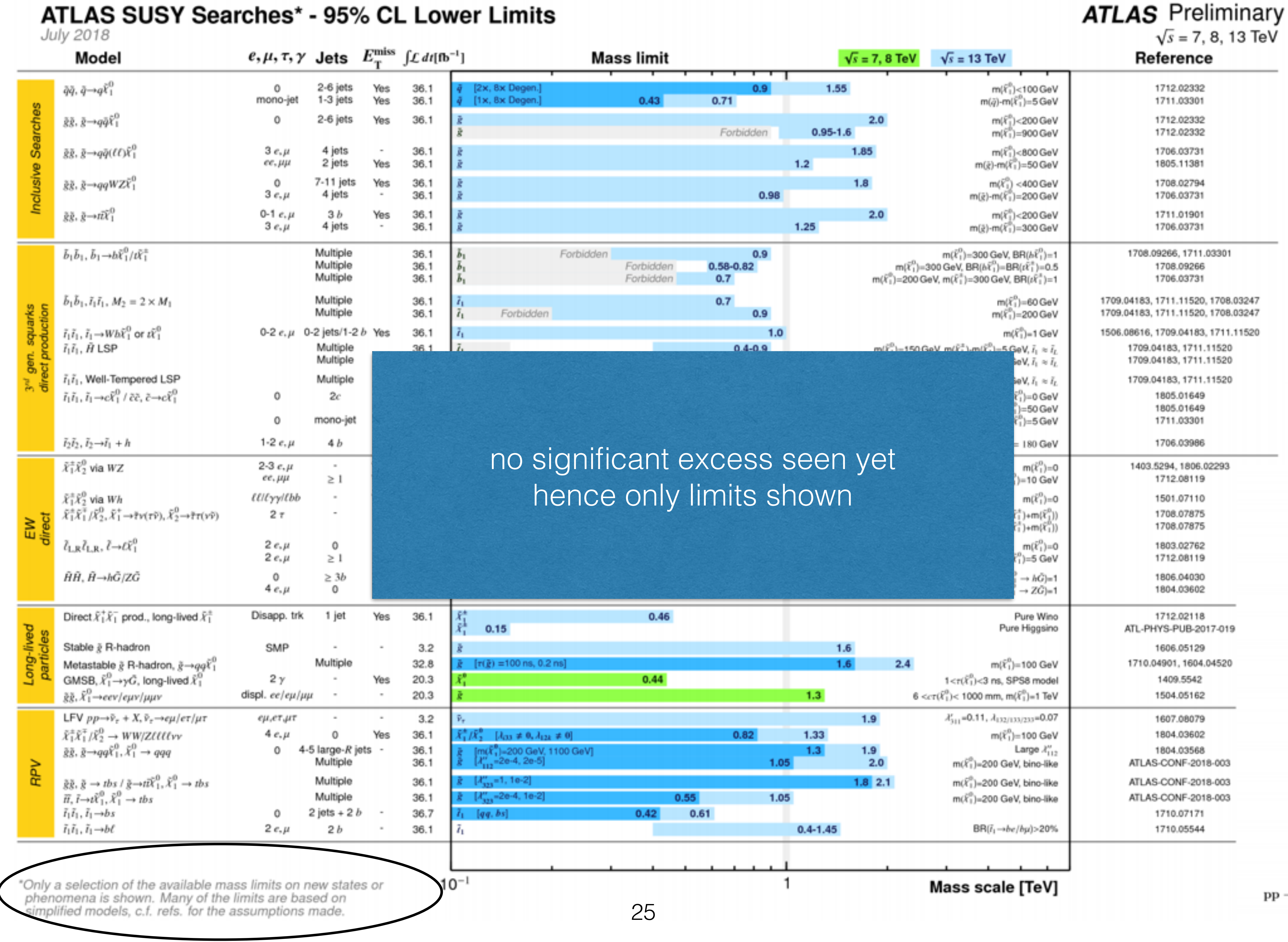
ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	$m(\tilde{\chi}_1^0)$<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	$m(\tilde{q})-m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	$m(\tilde{\chi}_1^0)$=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	$m(\tilde{\chi}_1^0)$<800 GeV	1706.03731
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	$m(\tilde{\chi}_1^0)$ <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=200 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=300 GeV	1706.03731
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{\chi}_1^0/t\tilde{\chi}_1^{\pm}$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=300 GeV, BR$(b\tilde{\chi}_1^0)$=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	$m(\tilde{\chi}_1^0)$=300 GeV, BR$(b\tilde{\chi}_1^0)$=BR$(t\tilde{\chi}_1^{\pm})$=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	$m(\tilde{\chi}_1^0)$=200 GeV, $m(\tilde{\chi}_1^{\pm})$=300 GeV, BR$(t\tilde{\chi}_1^{\pm})$=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	$m(\tilde{\chi}_1^0)$=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	$m(\tilde{\chi}_1^0)$=300 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	$m(\tilde{\chi}_1^0)$=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\rightarrow\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.6	$m(\tilde{\chi}_1^0)$=0	1403.5294, 1806.02293
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.17	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=10 GeV	1712.08119
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.26	$m(\tilde{\chi}_1^0)$=0	1501.07110
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.76	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5$(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1708.07875
						$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.22	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=100 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5$(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	$m(\tilde{\chi}_1^0)$=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	$m(\tilde{\ell})-m(\tilde{\chi}_1^0)$=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\rightarrow h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR$(\tilde{\chi}_1^0 \rightarrow h\tilde{G})$=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR$(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})$=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^{\pm}$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	$m(\tilde{\chi}_1^0)$=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, $m(\tilde{\chi}_1^0)$=1 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ [$\lambda_{133} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	$m(\tilde{\chi}_1^0)$=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow tbs / \tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR$(\tilde{t}_1\rightarrow be/b\mu)$>20%	1710.05544

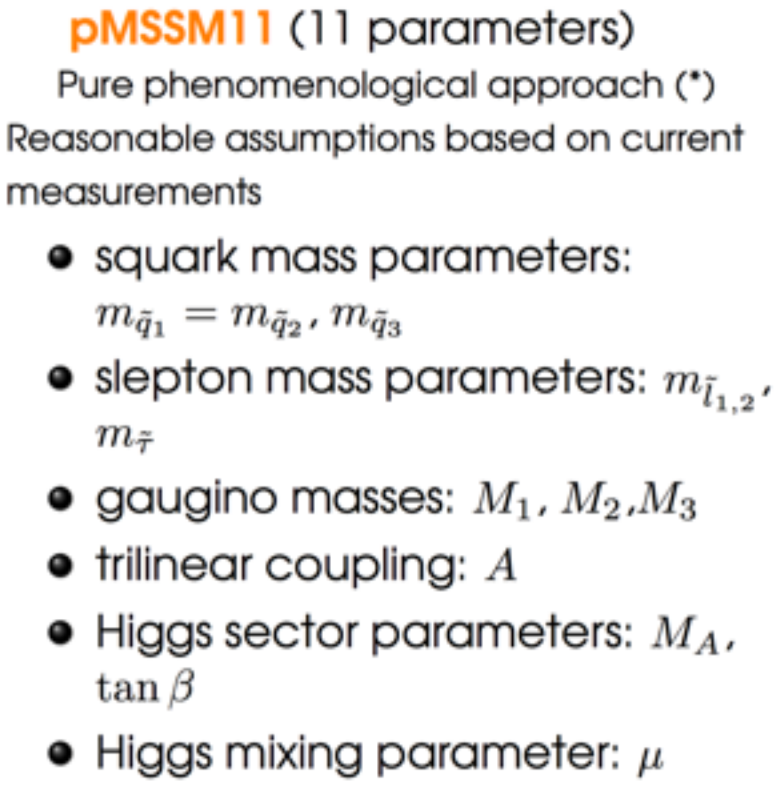
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



no significant excess seen yet
hence only limits shown

Eur. Phys. J. C (2018) 78:256

viable SUSY models: pMSSM



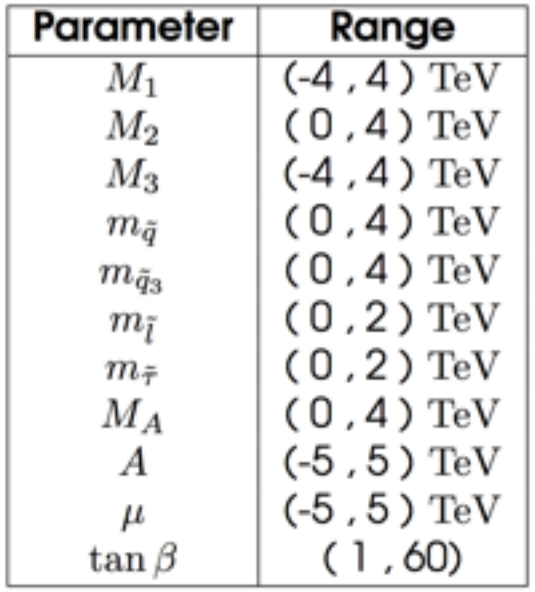
pMSSM11 (11 parameters)

Pure phenomenological approach (*)

Reasonable assumptions based on current measurements

- squark mass parameters: $m_{\tilde{q}_1} = m_{\tilde{q}_2}$, $m_{\tilde{q}_3}$
- slepton mass parameters: $m_{\tilde{l}_{1,2}}$, $m_{\tilde{\tau}}$
- gaugino masses: M_1, M_2,M_3
- trilinear coupling: A
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing parameter: μ

is only one of many possible selections. Results will depend on the choice of free parameters.

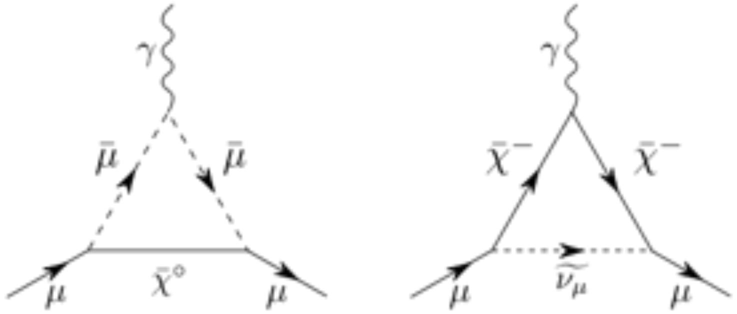


Parameter	Range
M_1	(-4 , 4) TeV
M_2	(0 , 4) TeV
M_3	(-4 , 4) TeV
$m_{\tilde{q}}$	(0 , 4) TeV
$m_{\tilde{q}_3}$	(0 , 4) TeV
$m_{\tilde{l}}$	(0 , 2) TeV
$m_{\tilde{\tau}}$	(0 , 2) TeV
M_A	(0 , 4) TeV
A	(-5 , 5) TeV
μ	(-5 , 5) TeV
$\tan\beta$	(1 , 60)

w/ and w/o (g_μ-2) result (*).
scanned 2 10^9 points
in parameter space.

only partial Run-2 LHC data included (36 fb-1)

(*) magnetic moment of $\mu = g_\mu\, e/2m\, S$ measured at BNL (E821) in 2006 to be 3.6 sigma away from SM expected value
Possible explanation: new heavy particles (SUSY?)



Eur. Phys. J. C (2018) 78:256

pMSSM11

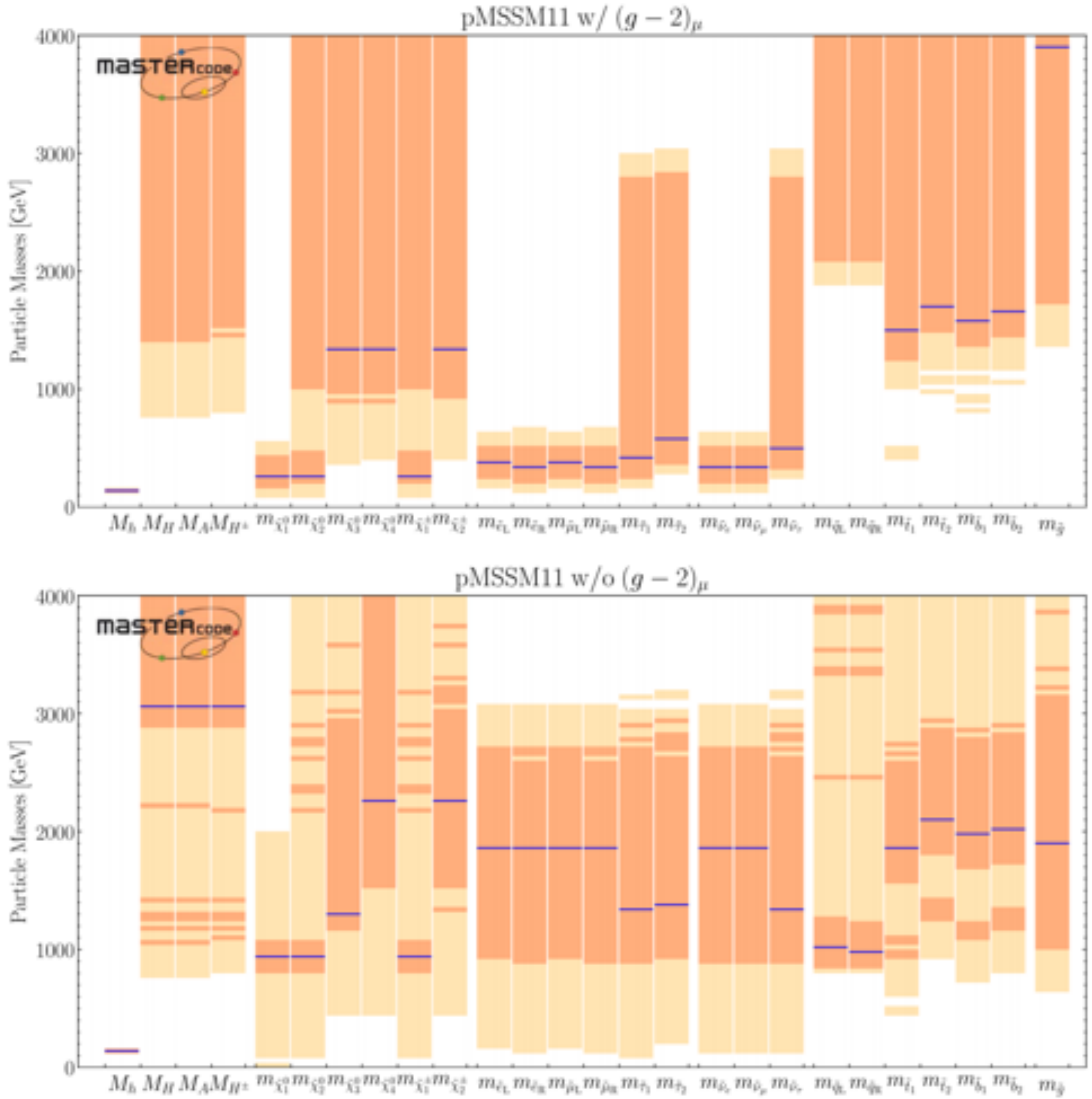
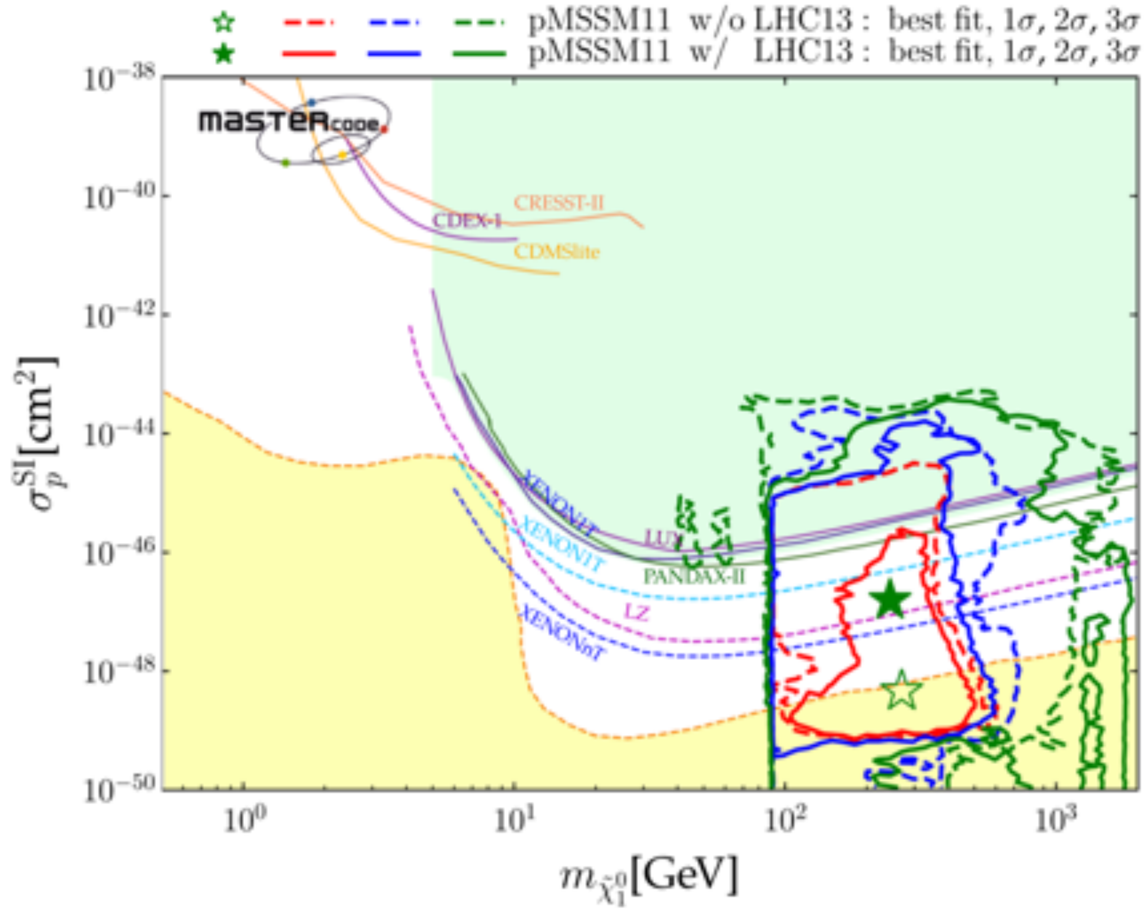


Fig. 23 Higgs and sparticle spectrum for the pMSSM11 with and without the $(g-2)_\mu$ constraint applied (upper and lower panels, respectively). The values at the best-fit points are indicated by blue lines, the 68% CL ranges by orange bands, and the 95% CL ranges by yellow bands

uses LHC partial Run-2 (13 TeV) data, 36 fb-1



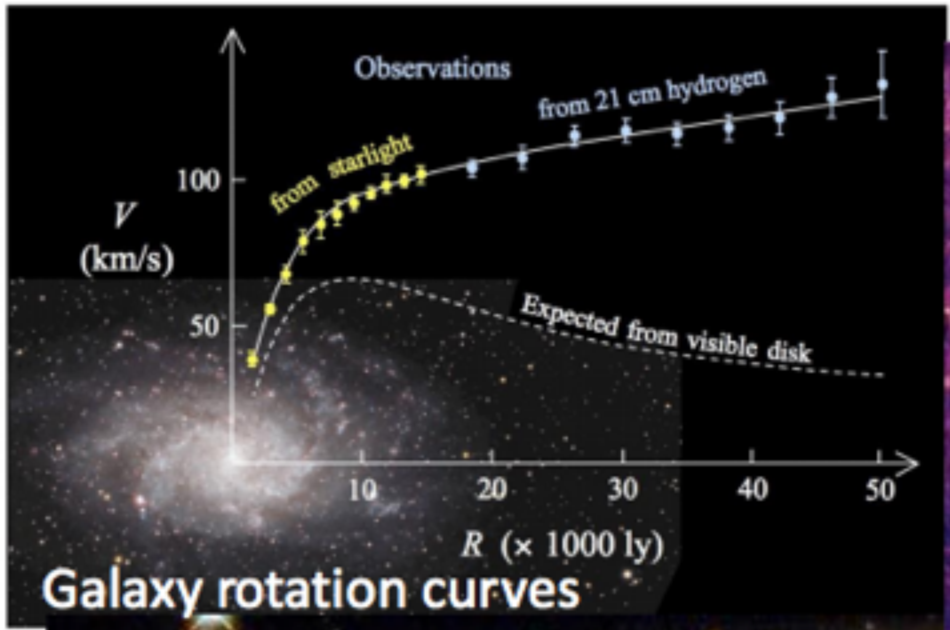
these mass ranges
are accessible at LHC
runs or at future colliders

also, soon g-2 experiment
at Fermilab will take data

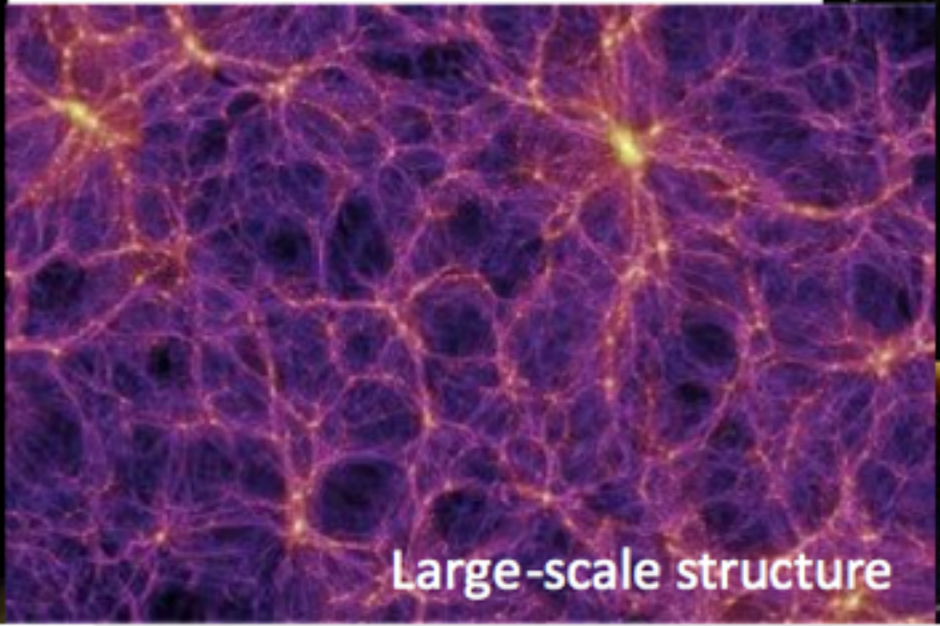
the search continues !

- DM searches

Dark Matter?

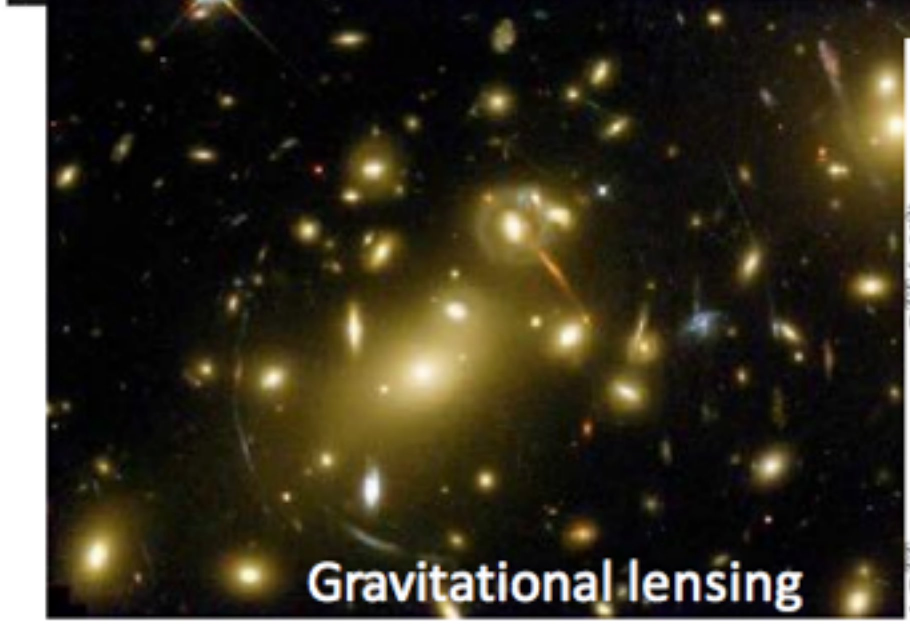


Galaxy rotation curves

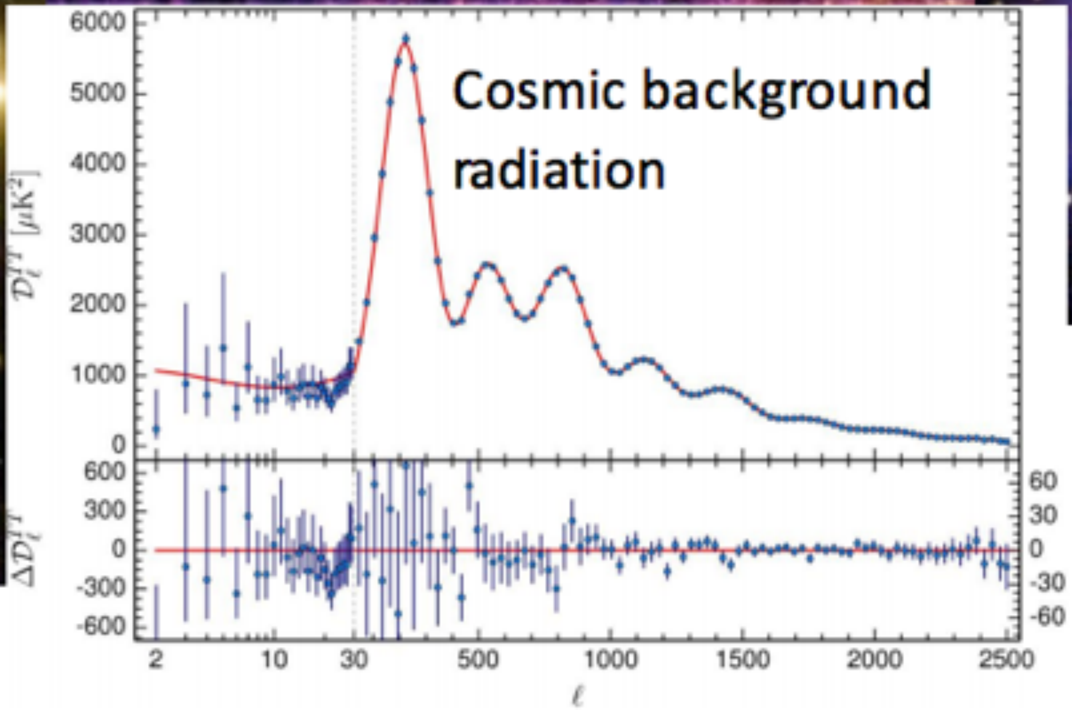


Large-scale structure

Dwarf galaxies



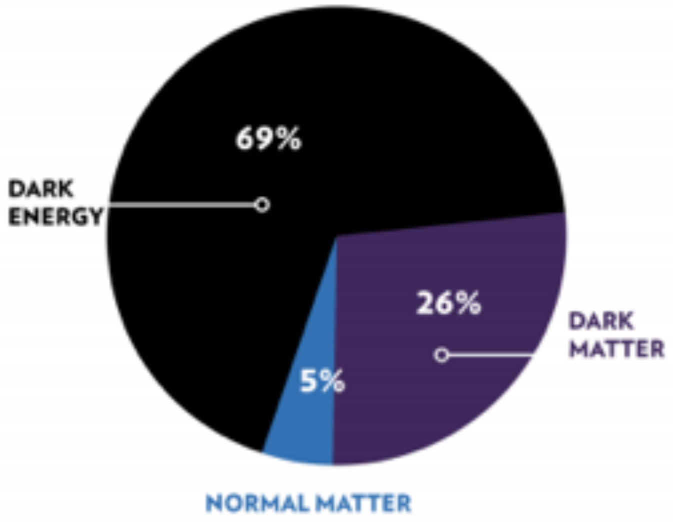
Gravitational lensing



Cosmic background radiation

Bullet clusters

ENERGY DISTRIBUTION OF THE UNIVERSE

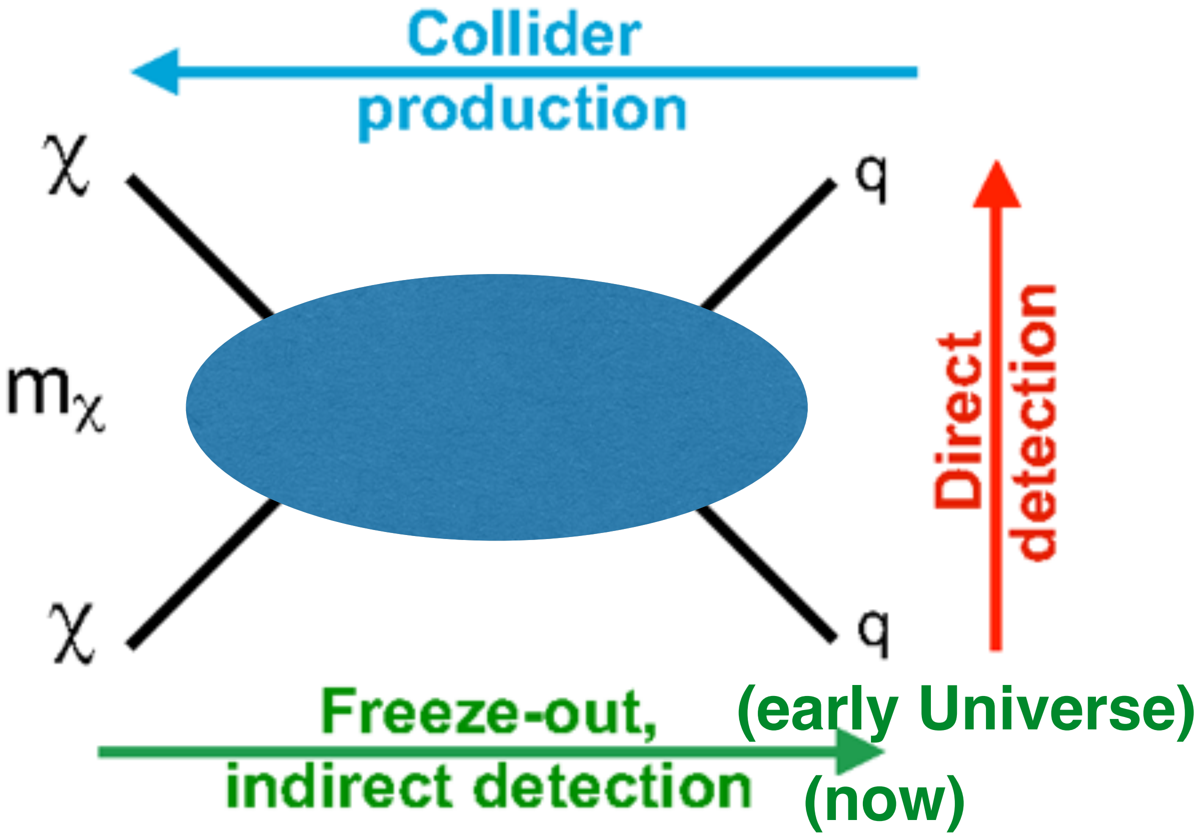


Abundant evidence for the presence of dark sector

No corresponding entity in the Standard Model

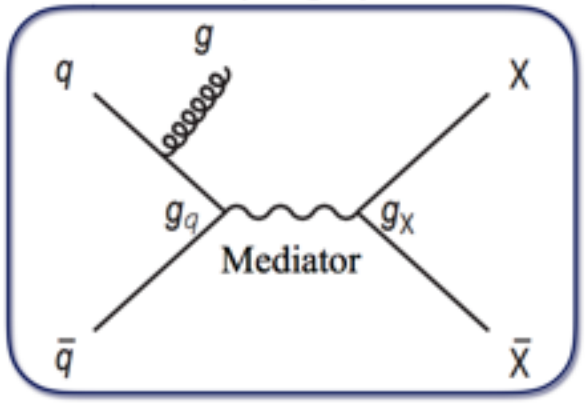
→ Dark Matter

Dark Matter searches



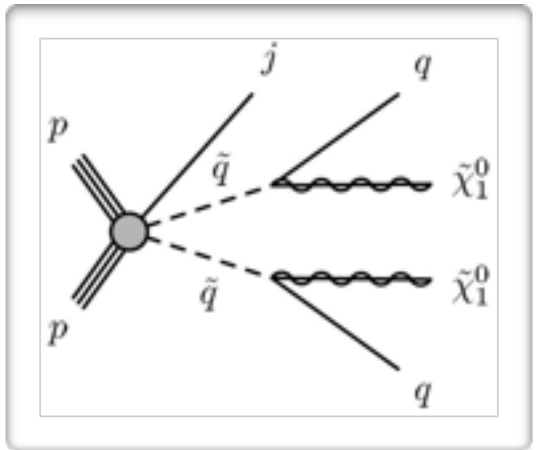
at colliders (LHC: ATLAS/CMS):
Direct search for WIMP &
mediator particles

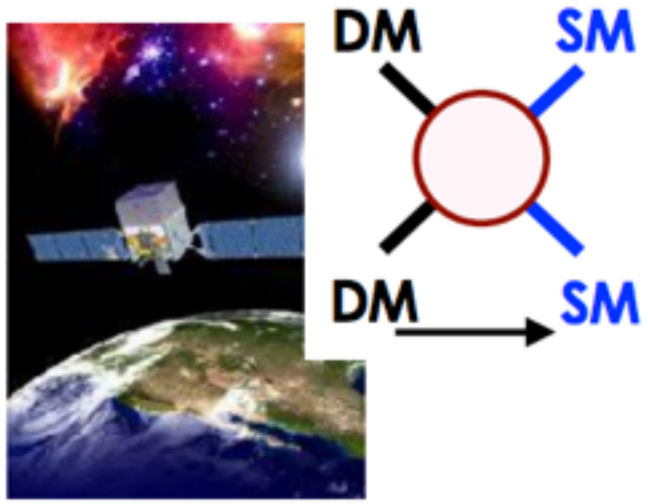
Simplified Models with only relevant couplings/particles



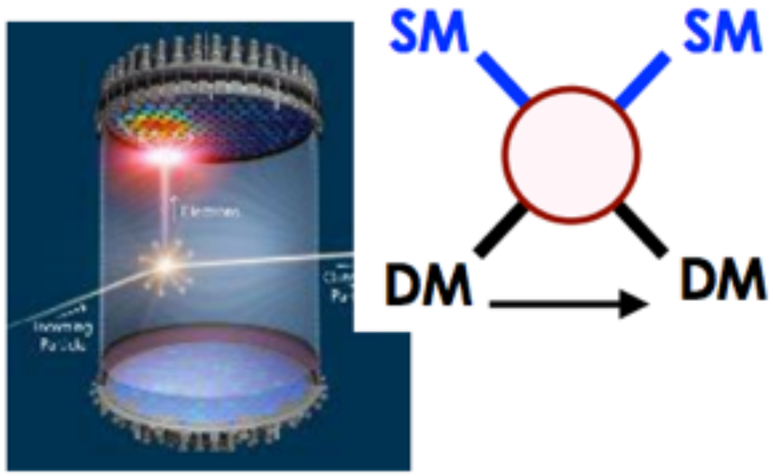
- Described in terms of Lorentz structure, m , m_{med}, g and g_q

Complete theories
many parameters,
exclusive searches

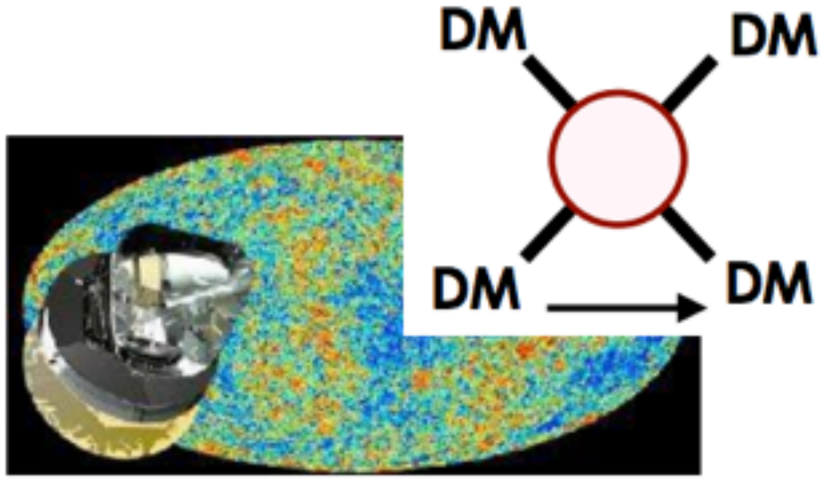




Indirect detection

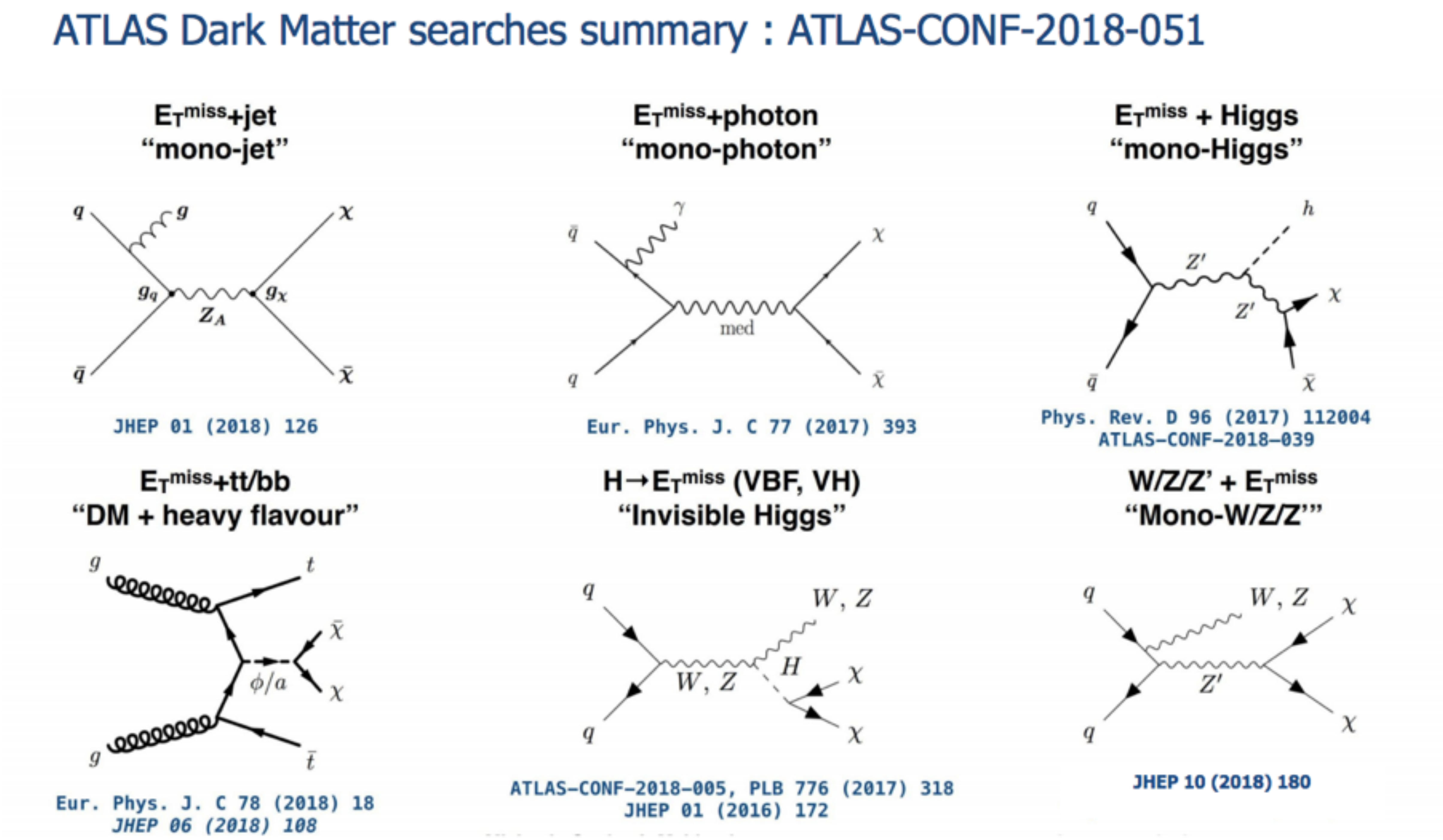


Direct detection



Astrophysical probes

Dark matter searches



ATLAS Dark Matter searches summary : ATLAS-CONF-2018-051

E_T^{miss}+jet
“mono-jet”

JHEP 01 (2018) 126

E_T^{miss}+photon
“mono-photon”

Eur. Phys. J. C 77 (2017) 393

E_T^{miss} + Higgs
“mono-Higgs”

Phys. Rev. D 96 (2017) 112004
ATLAS-CONF-2018-039

E_T^{miss}+tt/bb
“DM + heavy flavour”

Eur. Phys. J. C 78 (2018) 18
JHEP 06 (2018) 108

H→E_T^{miss} (VBF, VH)
“Invisible Higgs”

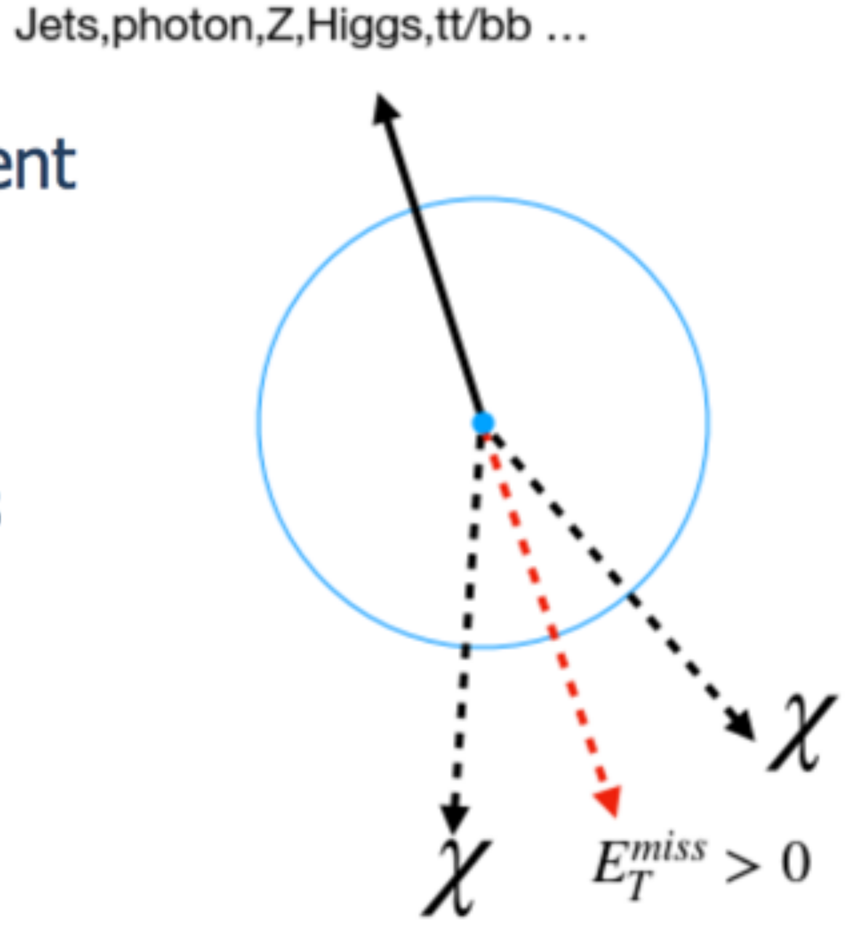
ATLAS-CONF-2018-005, PLB 776 (2017) 318
JHEP 01 (2016) 172

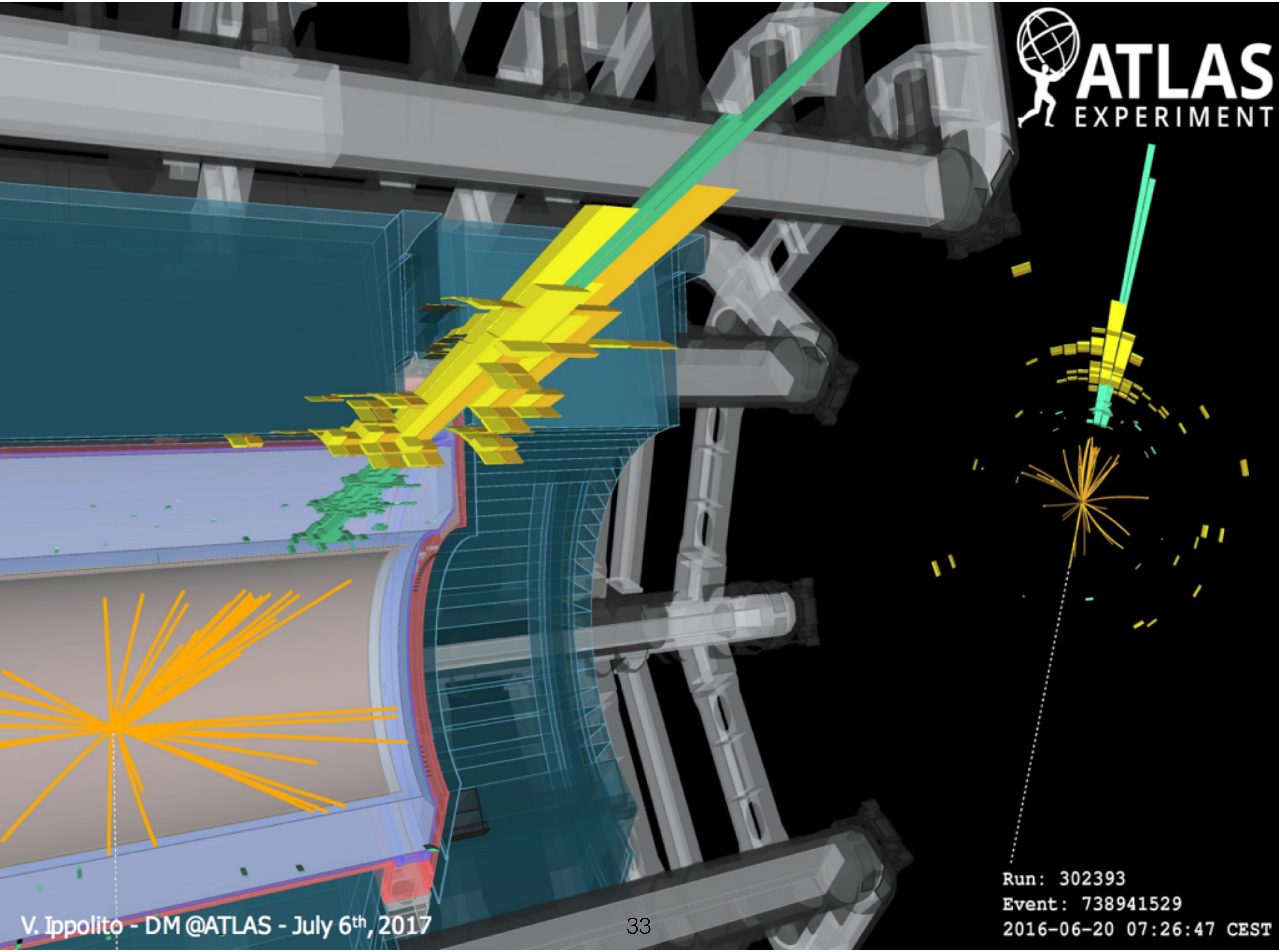
W/Z/Z’ + E_T^{miss}
“Mono-W/Z/Z’”

JHEP 10 (2018) 180

Mono-X searches

- Use known SM process to tag the event and look for invisible DM particles via their E_T^{miss} signature
  - Tagging can be via an ISR process (jet, γ,…). Mono-X
  - Or a more complicated event with (bb, tt)

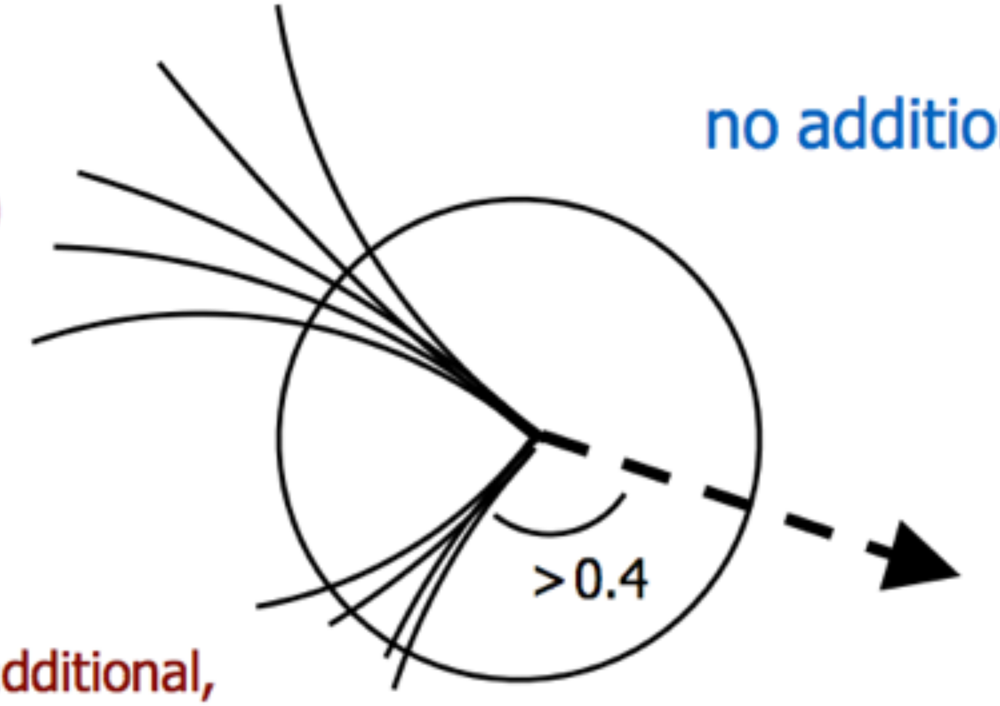



ATLAS EXPERIMENT
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Mono-jet

JHEP 01 (2018) 126

best channel if tagging object comes from ISR! (pay only α_s)



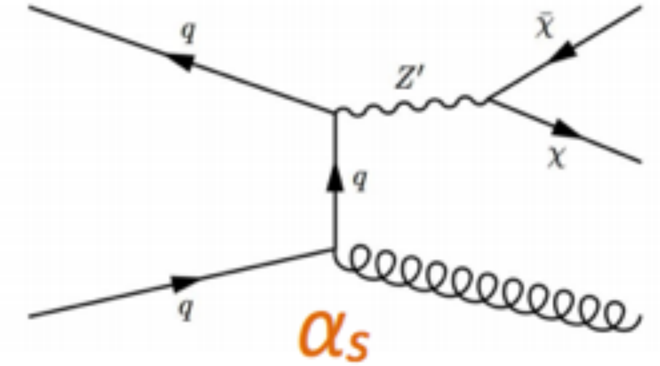
jet

high-pT (250 GeV)
central (|η|<~2.4)
high quality

no additional electron or muon

+trigger
MET > 70 GeV
(fully efficient above 200 GeV)

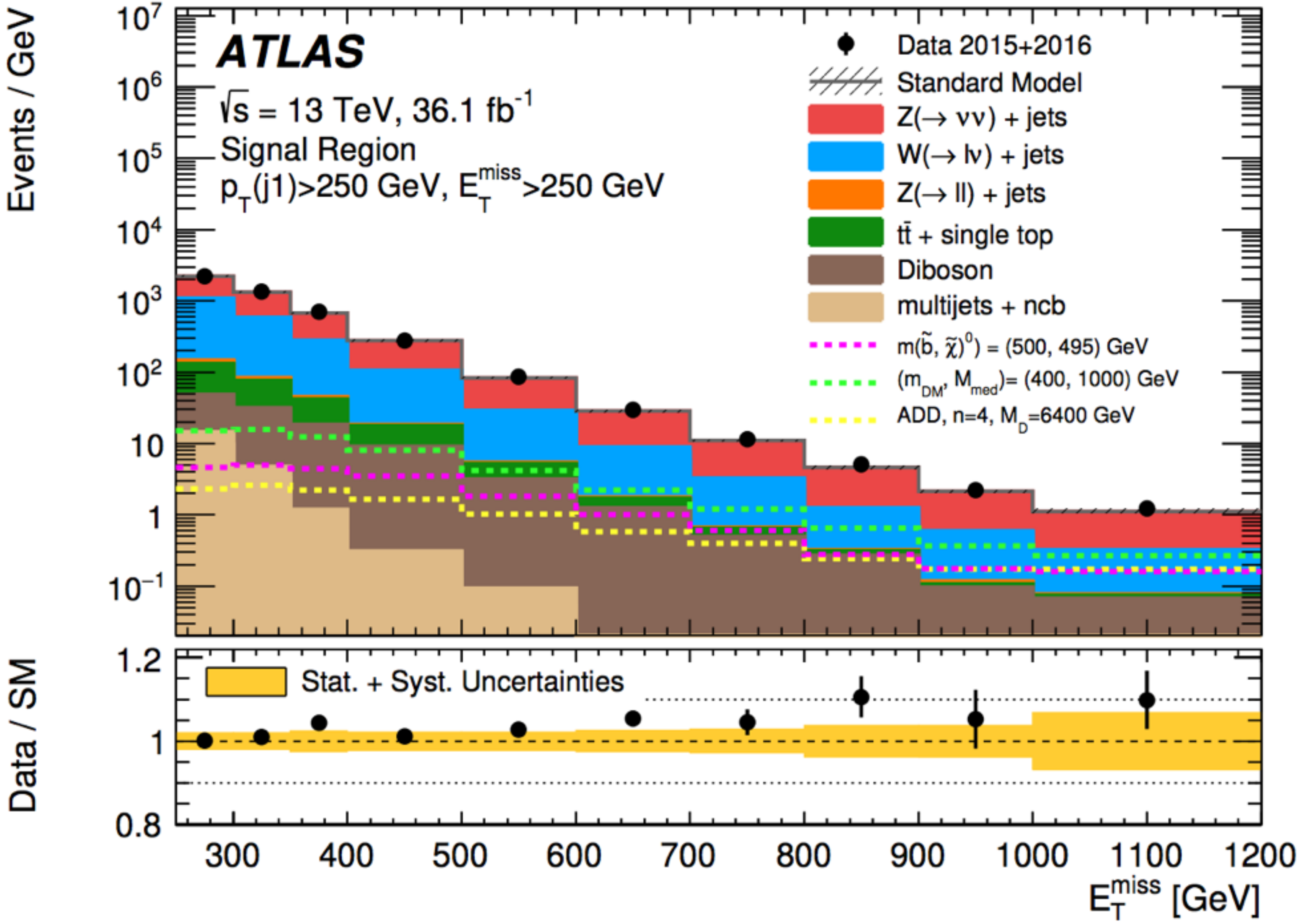
MET>250 GeV



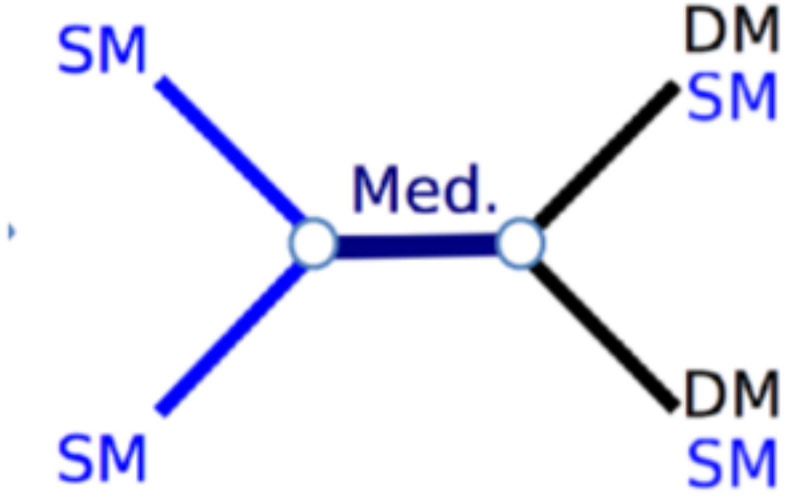
additional,
softer jets
(up to 3)

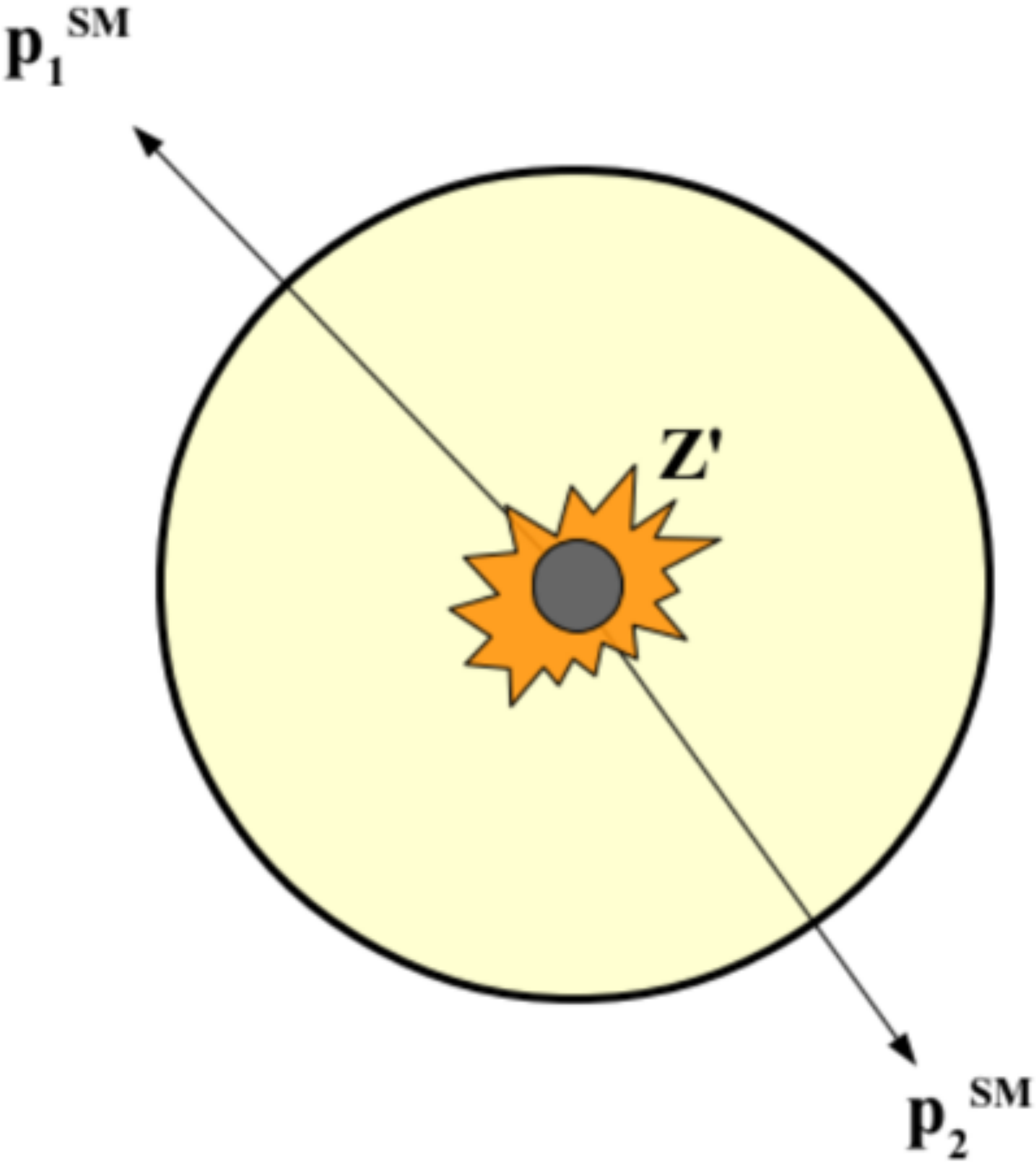
same signature as

- $Z(\nu\nu)$ + jets, $W(\tau_{had}\,\nu)$ + jets...
- normalization from simultaneous fit to p_T (W/Z) distributions in lepton control regions
- use calorimeter segmentation to reject beam & instrumental background


Events / GeV
ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Signal Region
p_T(j1)>250 GeV, E_T^{miss}>250 GeV
Data 2015+2016
Standard Model
Z(→ νν) + jets
W(→ lν) + jets
Z(→ ll) + jets
$t\bar{t}$ + single top
Diboson
multijets + ncb
m($\tilde{b}$, $\tilde{\chi}^0$) = (500, 495) GeV
(m_{DM}, M_{med})= (400, 1000) GeV
ADD, n=4, M_D=6400 GeV
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
Data / SM
Stat. + Syst. Uncertainties
1.2
1
0.8
300
400
500
600
700
800
900
1000
1100
1200
E_T^{miss} [GeV]

Mediator Searches





- Dark matter mediators can be produced at the LHC and possibly decay to SM particles
- Signal can be either a new resonance or an excess of events w-r-t SM processes

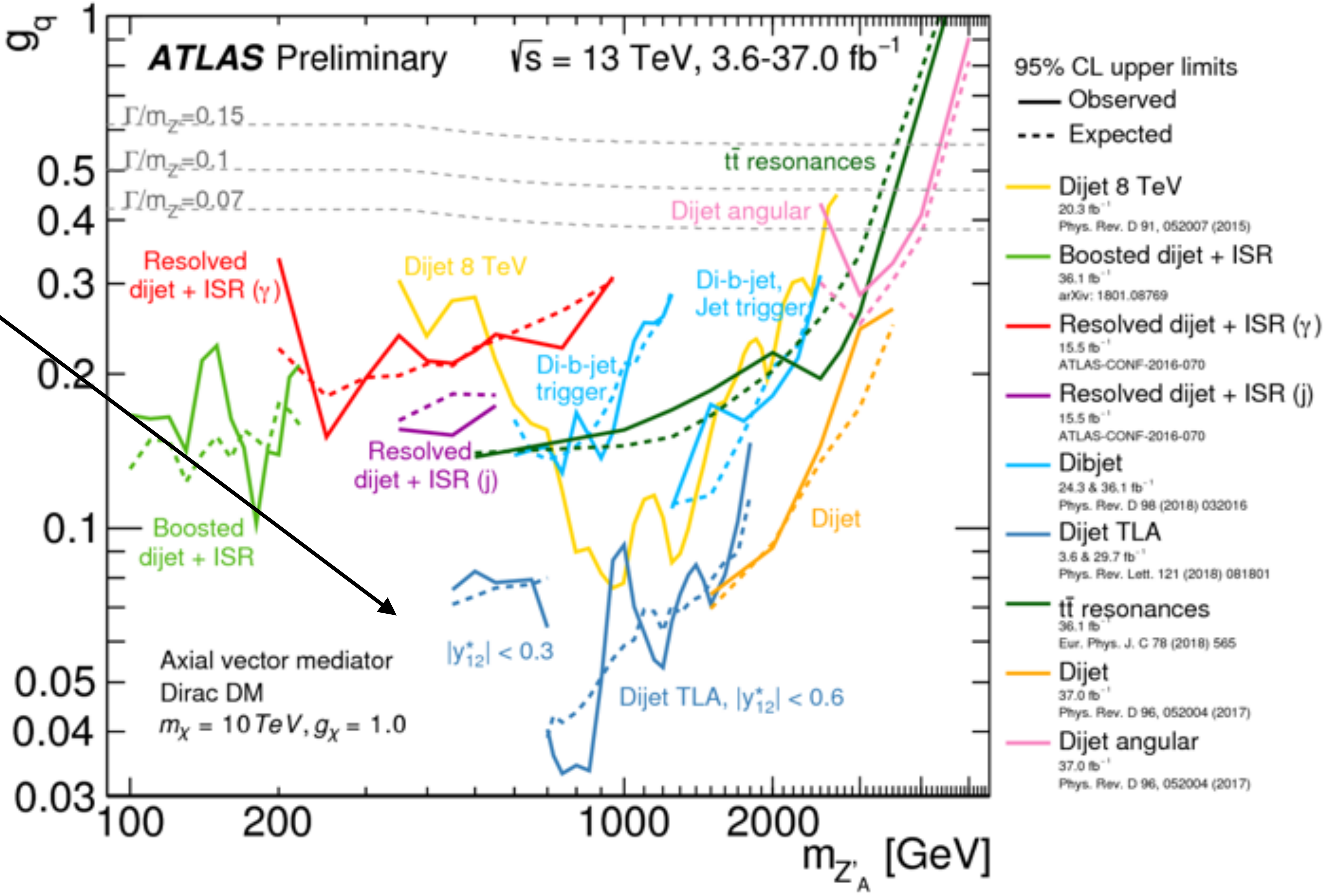
Phys. Rev. Lett. 121 (2018) 081801

Di-jet resonance searches

Use trigger objects Level Analysis (TLA) for “online” scouting

- Backgrounds & estimation: same strategy as the full dijet analysis, dedicated calibrations needed on TLA jets

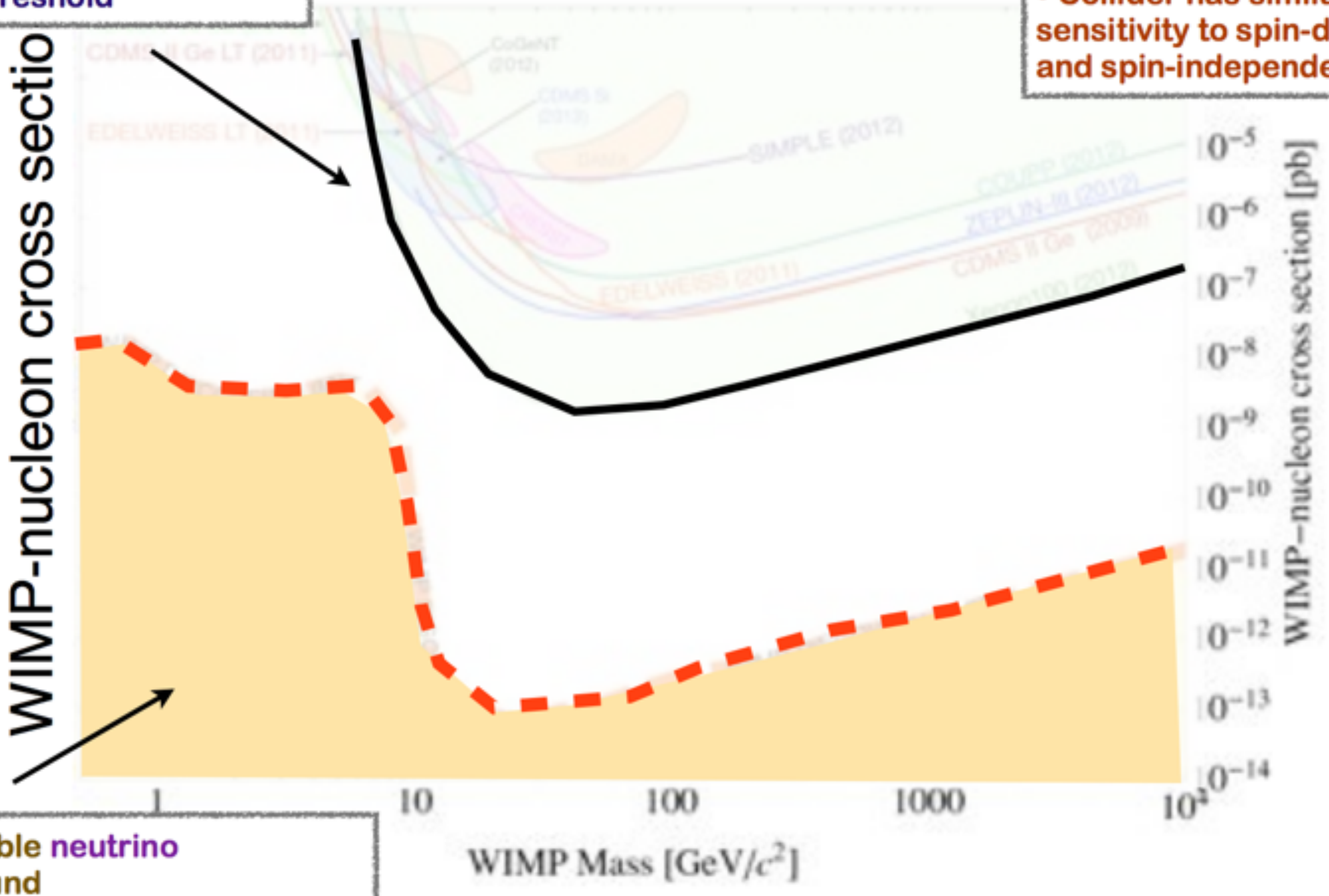
- Signal regions – lower kinematic reach than the dijet analysis, searching for lighter resonances



Challenges of direct detection experiments

- Low mass region difficult
- Collider does not have low energy threshold

- Much weaker sensitivity to Spin-dependent interactions.
- Collider has similar sensitivity to spin-dependent and spin-independent

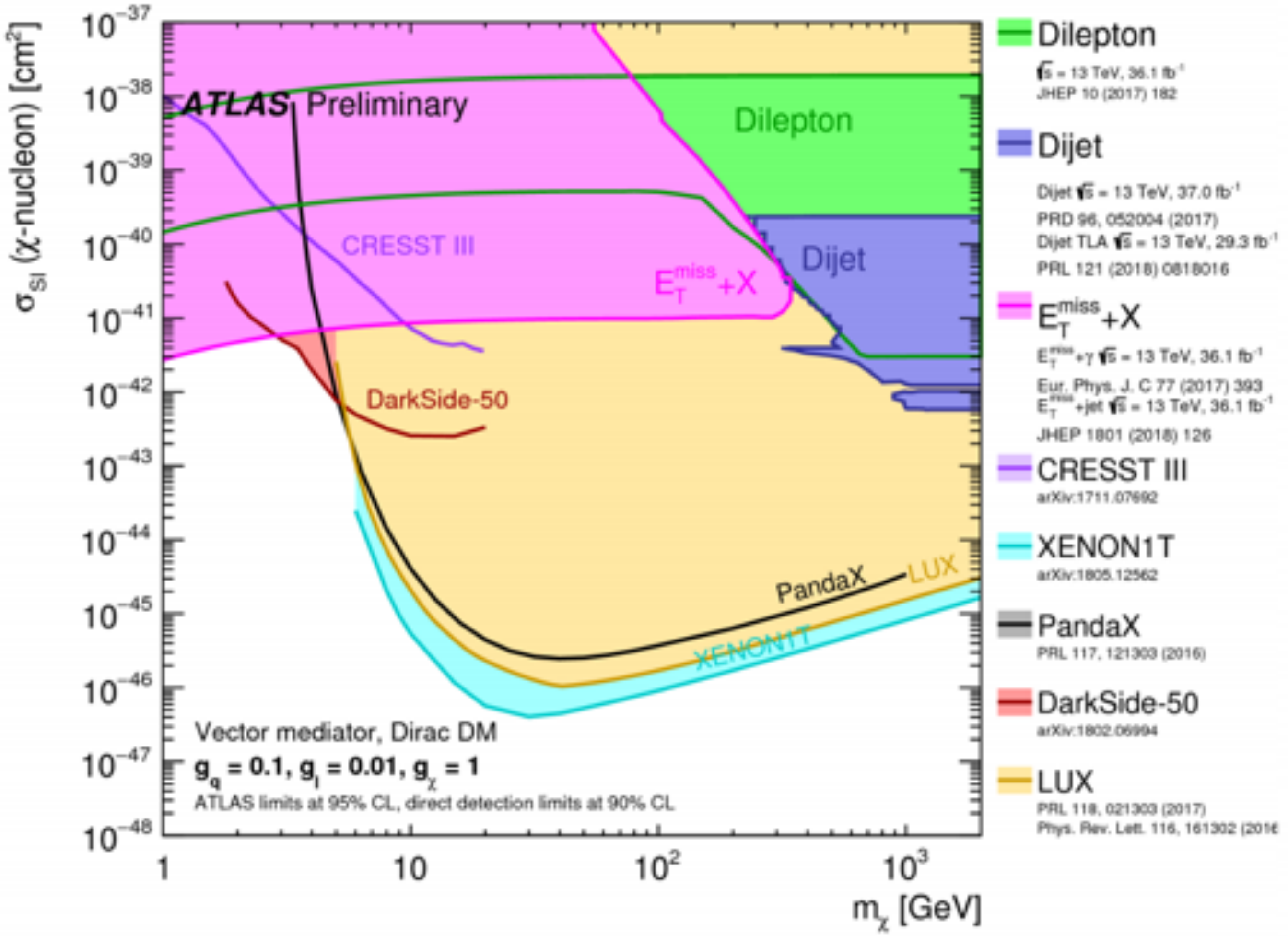


- Irreducible neutrino background
- WIMP discovery limit

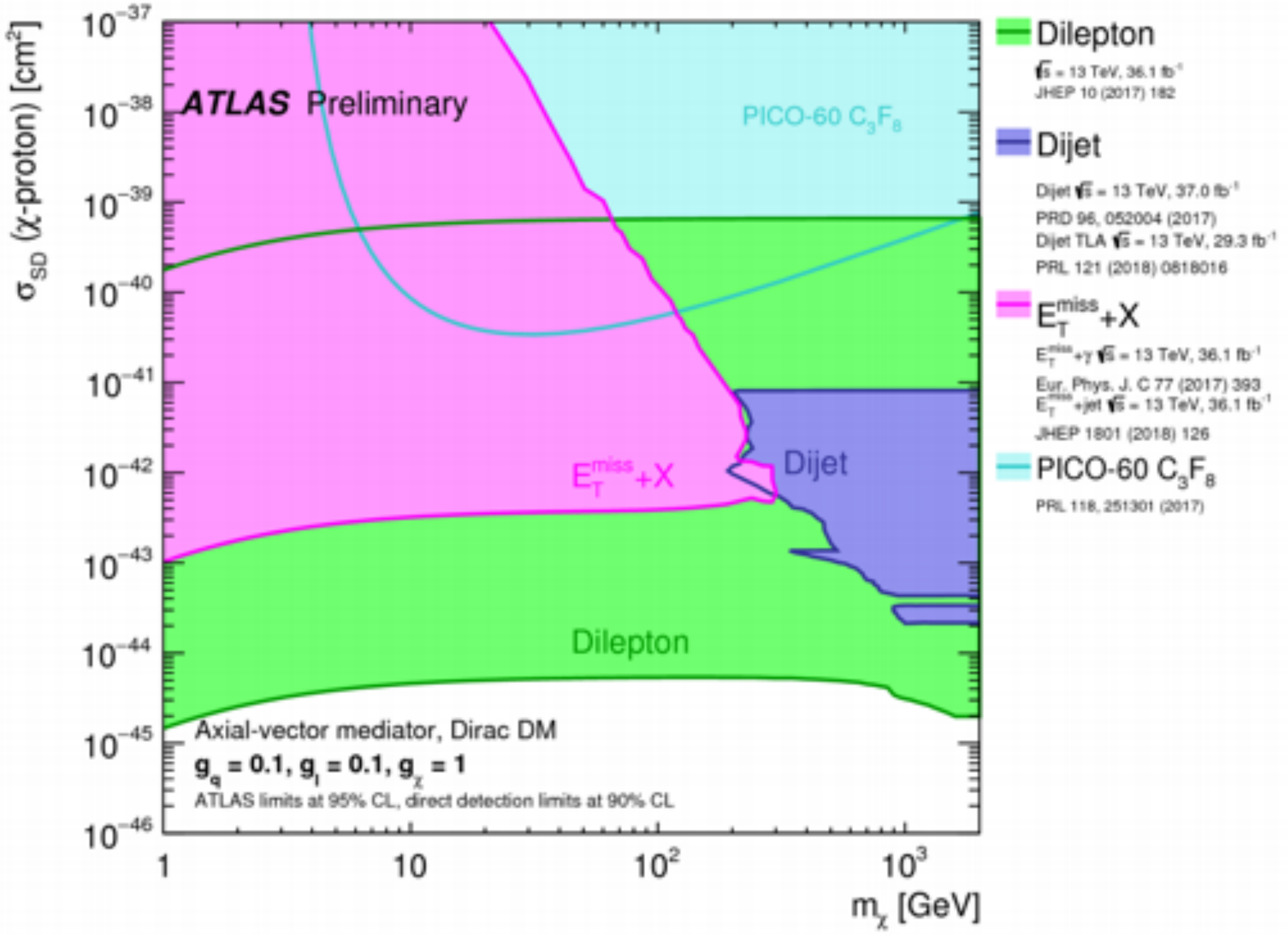
ATLAS-CONF-2018-051

Colliders complement direct searches

Spin-independent DM-nucleon cross section vs m_{DM}



Spin-dependent DM-proton cross section vs m_{DM}



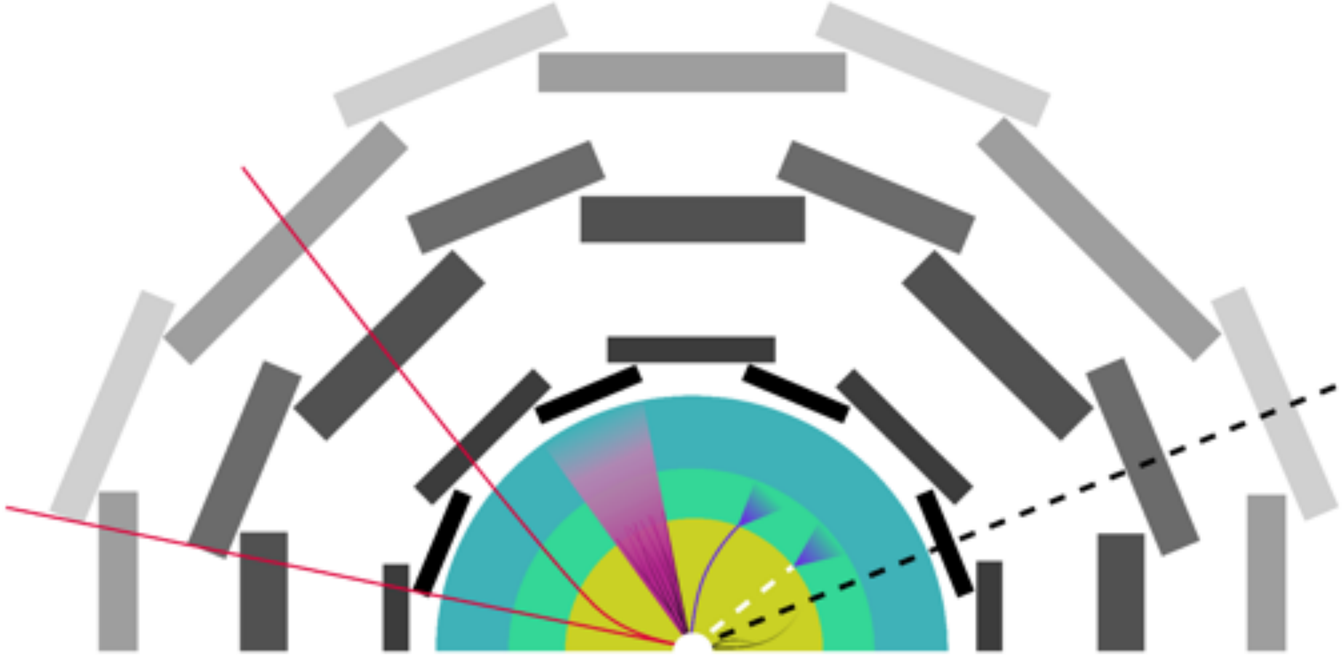
There are model assumptions in collider searches results. Generally they :

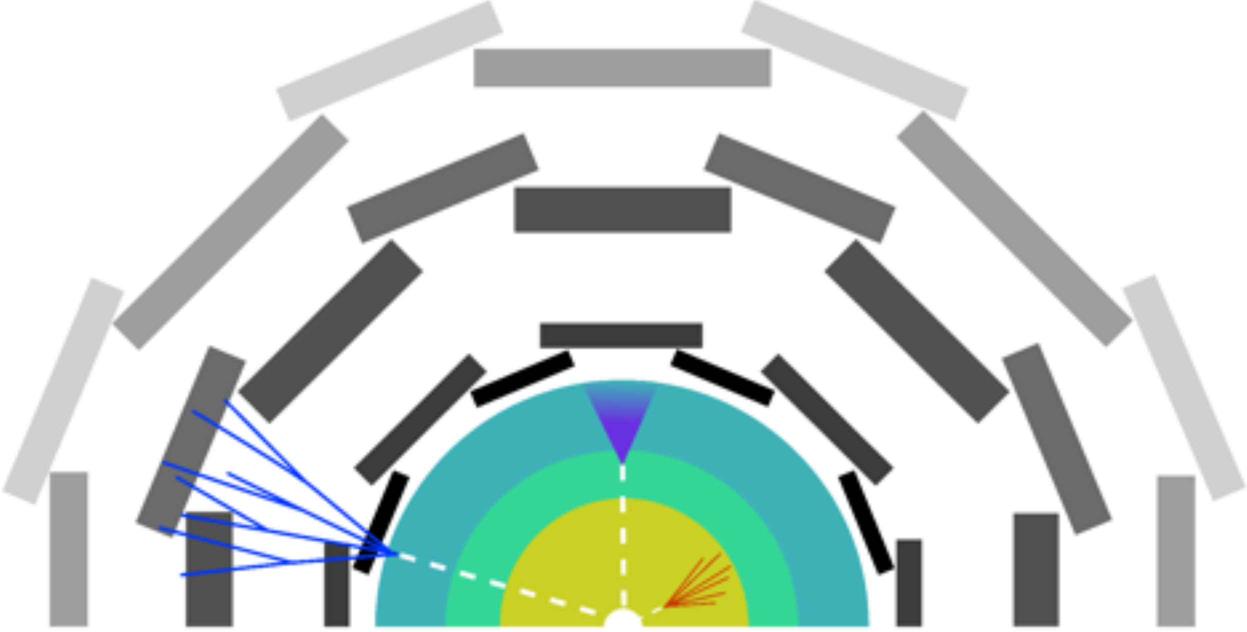
- are sensitive at low DM (<~5 GeV) for σSI(DM-nucleon). Spin-independent interaction cross-section with heavy nuclei is enhanced by A^2
- have ~3 orders of magnitude better sensitivity for σSD (DM-nucleon)

- Long Lived Particles

Being unconventional is the key word

conventional
final state particles





un-conventional
final state particles

why long lifetime?

Decays via heavy particle

e.g. μ to e via off-shell W

Limited phase space

e.g. K_{short} vs K_{long}

$m_{kaon} \sim m_{3\pi}$

Small couplings

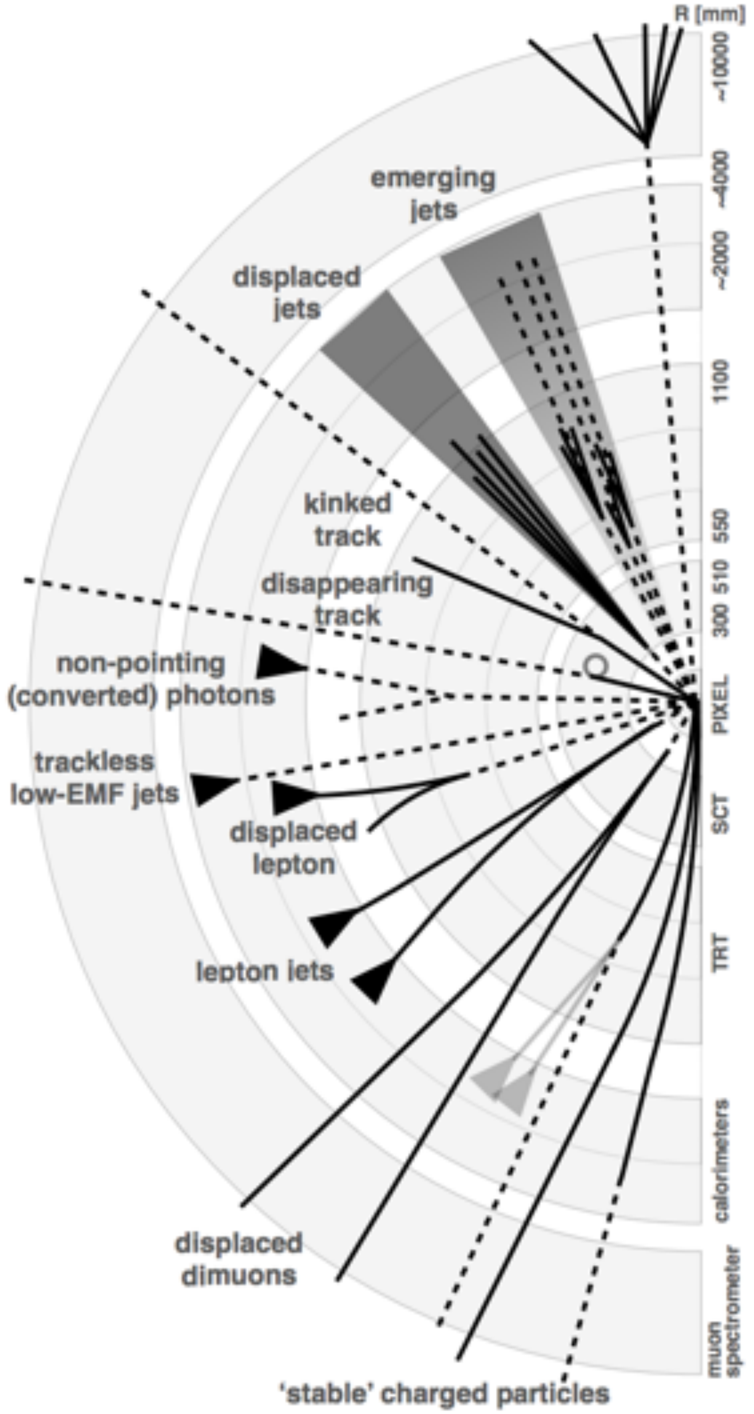
e.g. B meson decays via electroweak processes

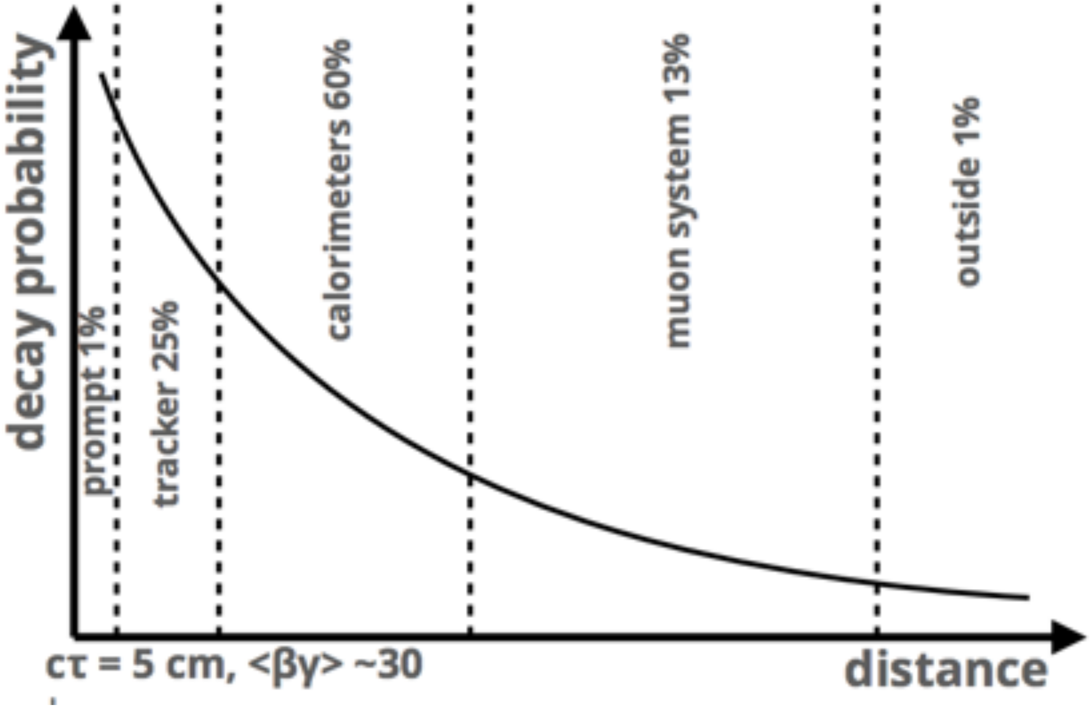
Unconventional

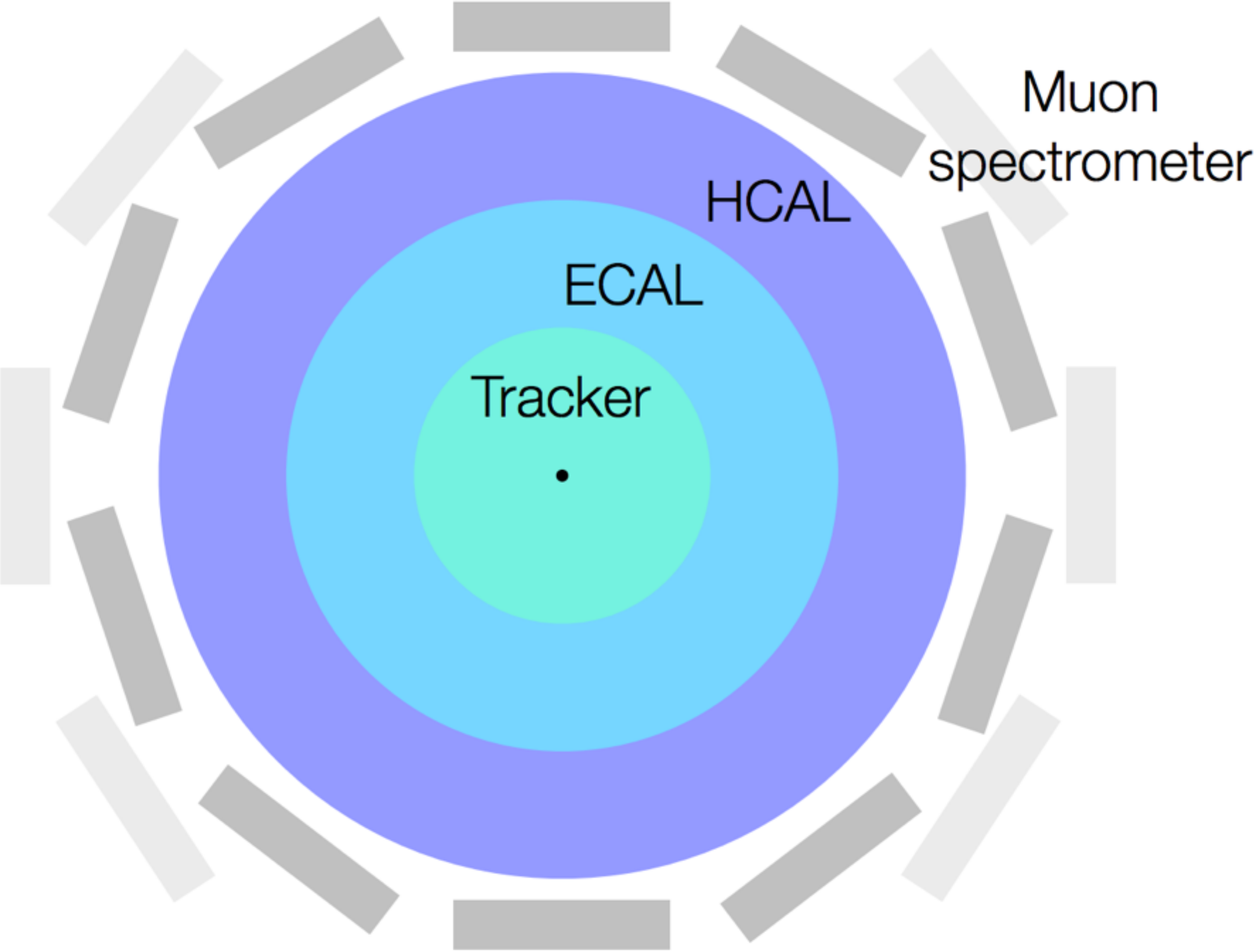
credit: S. Mehlhase
LLP Workshop - Amsterdam, 2018

Search for particles that display long lifetime
and still leave some signs within the detector volume

Multiple search strategies can be applied to one physics model, depending on the lifetime
(exp. distribution with constant cτ, proper lifetime).






Muon spectrometer
HCAL
ECAL
Tracker

first problem: trigger

In Run-1 and
Run-2 we thought
conventional at trigger:

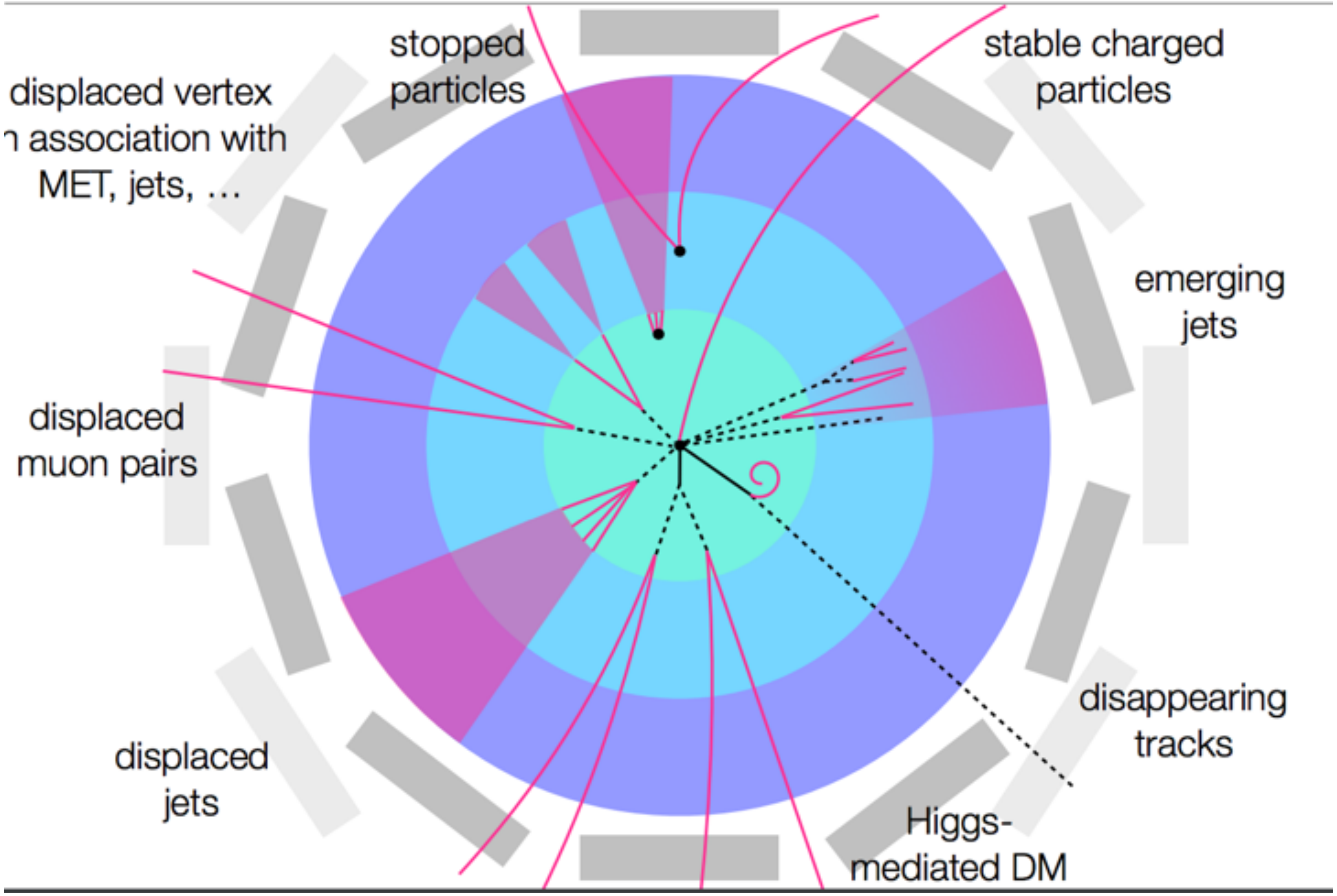
use:
HT (scalar sum of jets pT)

MET

Muon triggers

Calorimeter energy
in EM/Had ratio

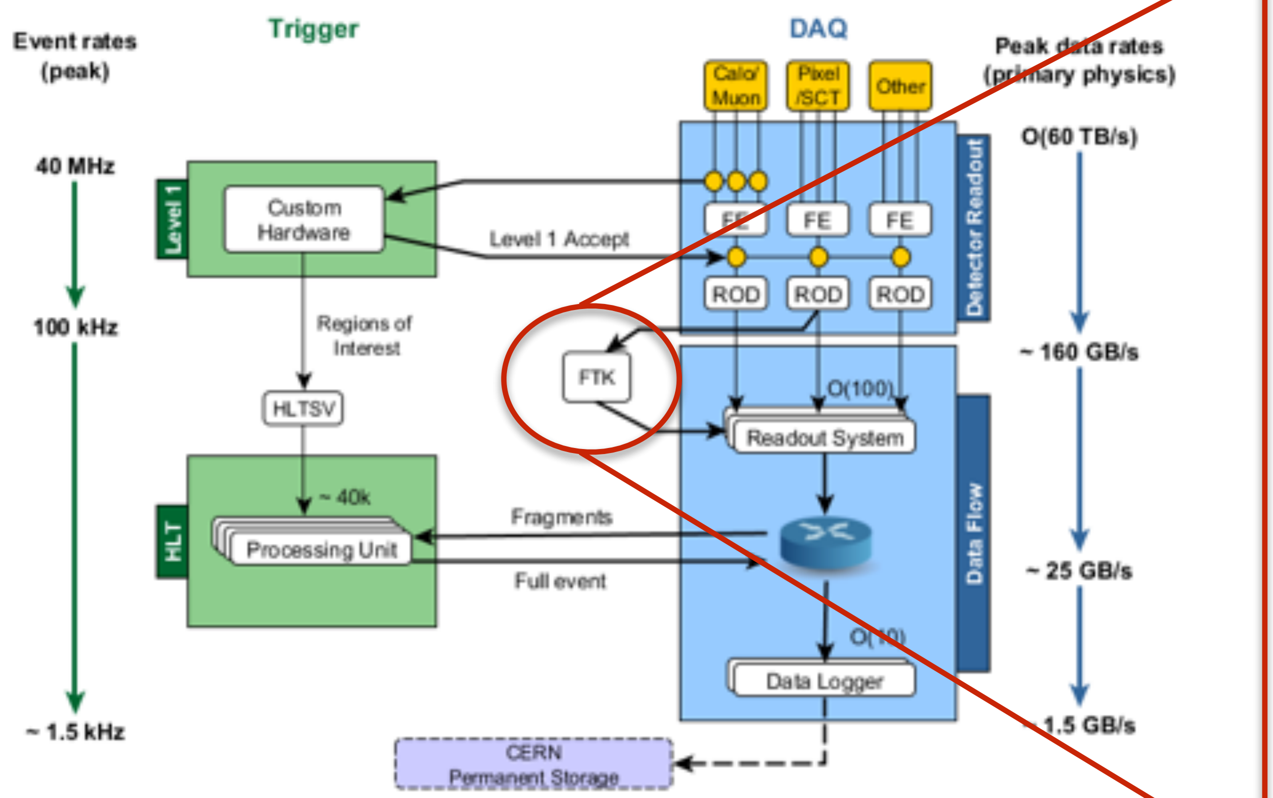
special tracking
reconstruction (large-radius
tracking)
or identificaion (dE/dx)
only in offline
and not for all data

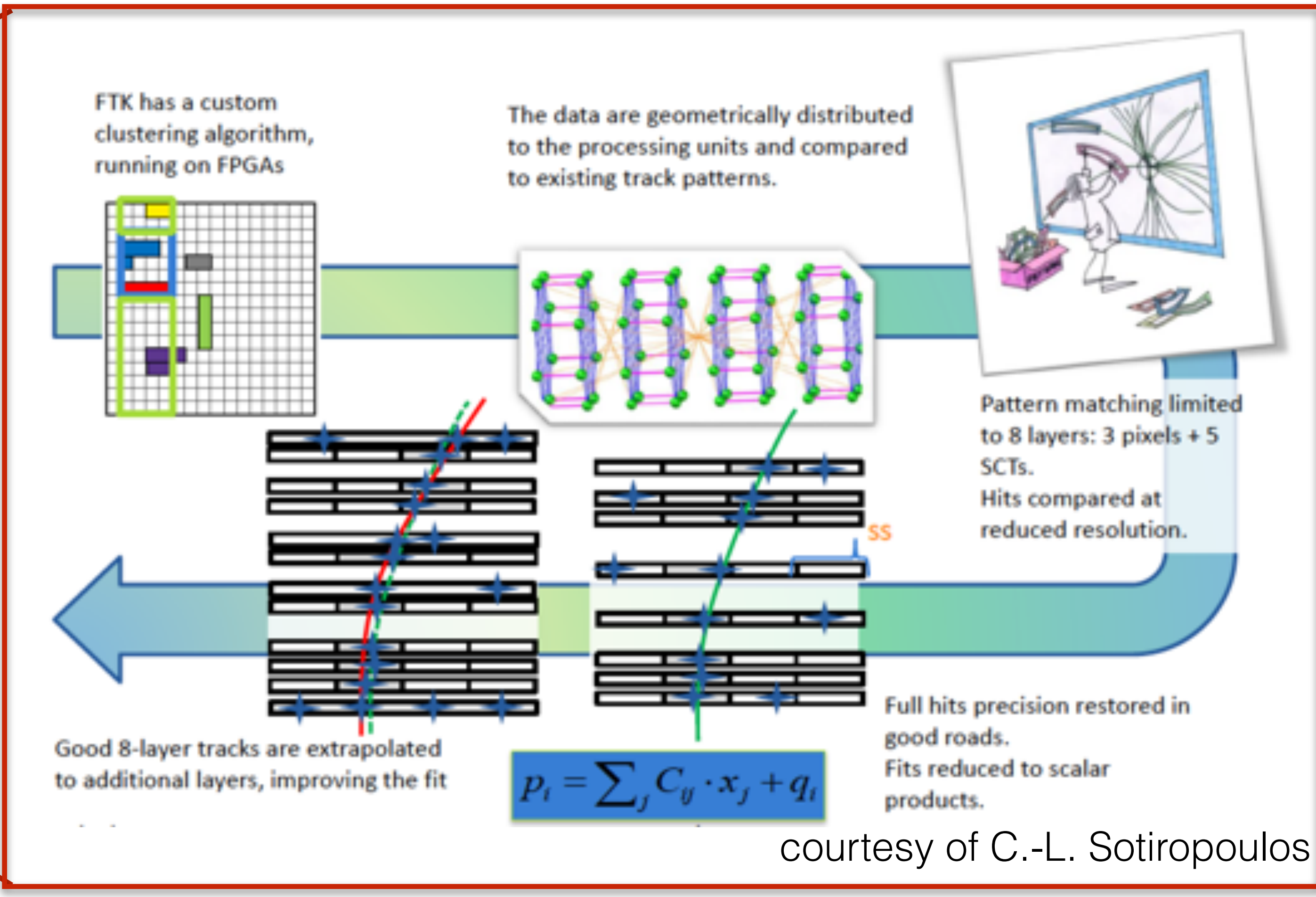


this limits physics reach in lifetime range and mass range that can be investigated.

how to improve for Run-3?

Trigger in Run-3





FTK has a custom clustering algorithm, running on FPGAs

The data are geometrically distributed to the processing units and compared to existing track patterns.

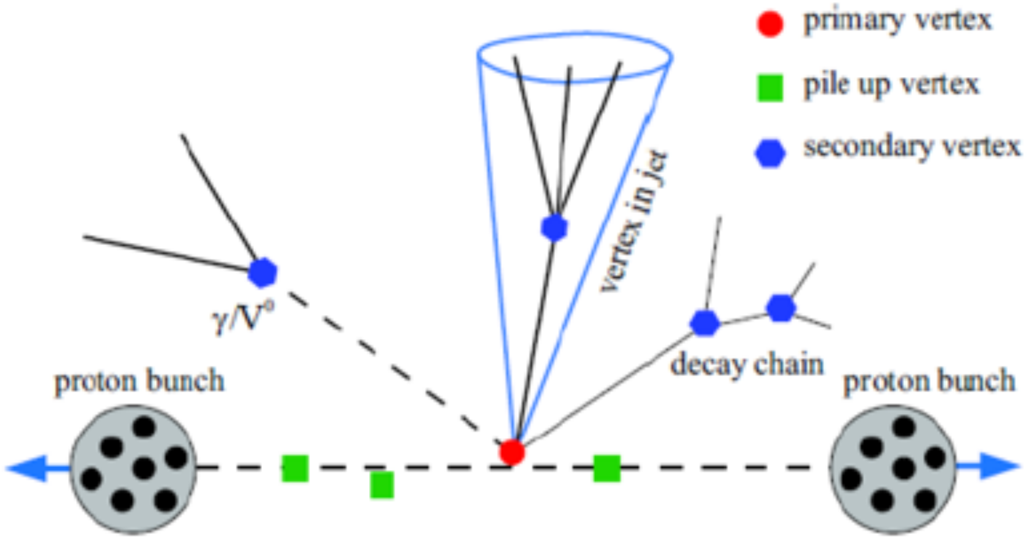
Pattern matching limited to 8 layers: 3 pixels + 5 SCTs.
Hits compared at reduced resolution.

Good 8-layer tracks are extrapolated to additional layers, improving the fit

$$p_i = \sum_j C_{ij} \cdot x_j + q_i$$

Full hits precision restored in good roads.
Fits reduced to scalar products.

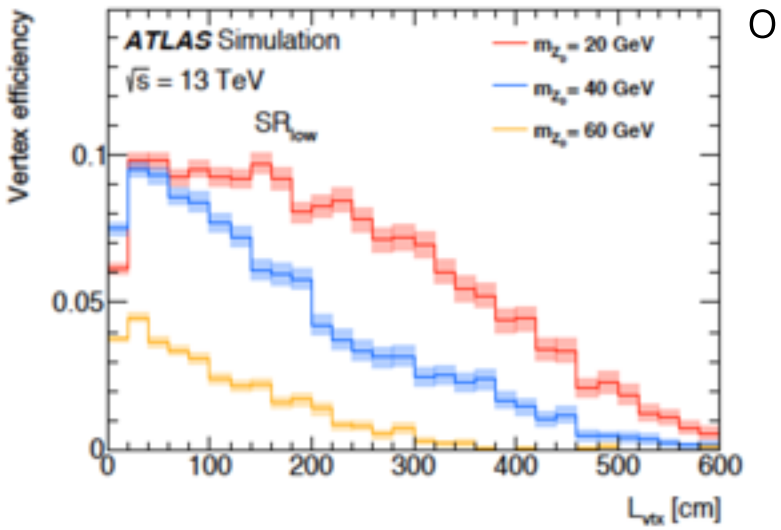
courtesy of C.-L. Sotiropoulos



full event track information analysable
within < 100 microseconds -> very fast !

- increases robustness to pile-up
- allows to use tracking information and achieve almost offline quality selection, right after L1
increases efficiency for complicated topologies, eg LLP

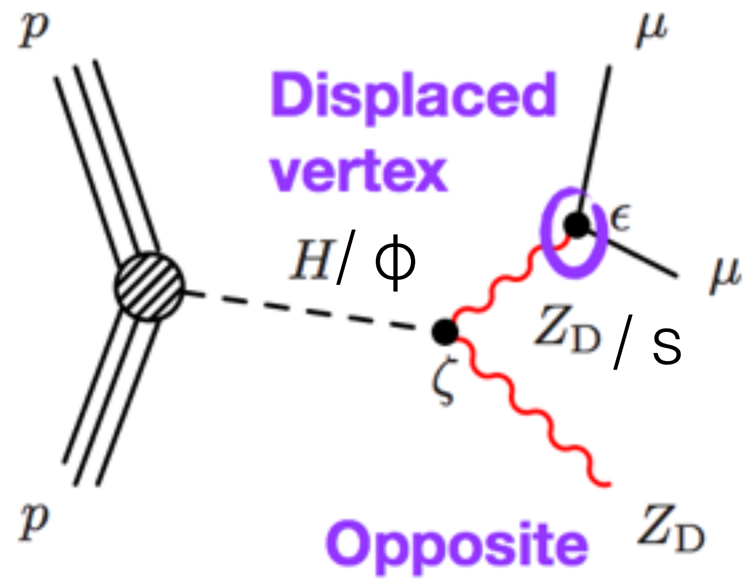
Dark photons/scalars to displaced muon pairs



only 10% at best

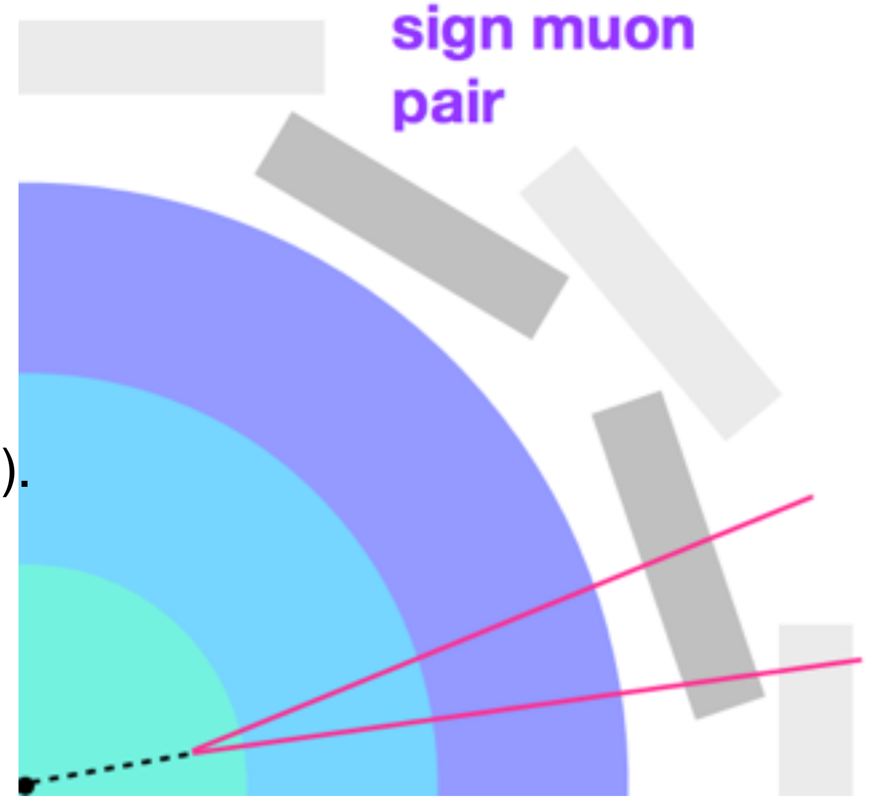
$c\tau_{Z_D} \sim 1/\varepsilon^2$, ε: mixing Z-$Z_D$

$\varepsilon \sim 10^{-5}$ —> long-lived



Displaced vertex

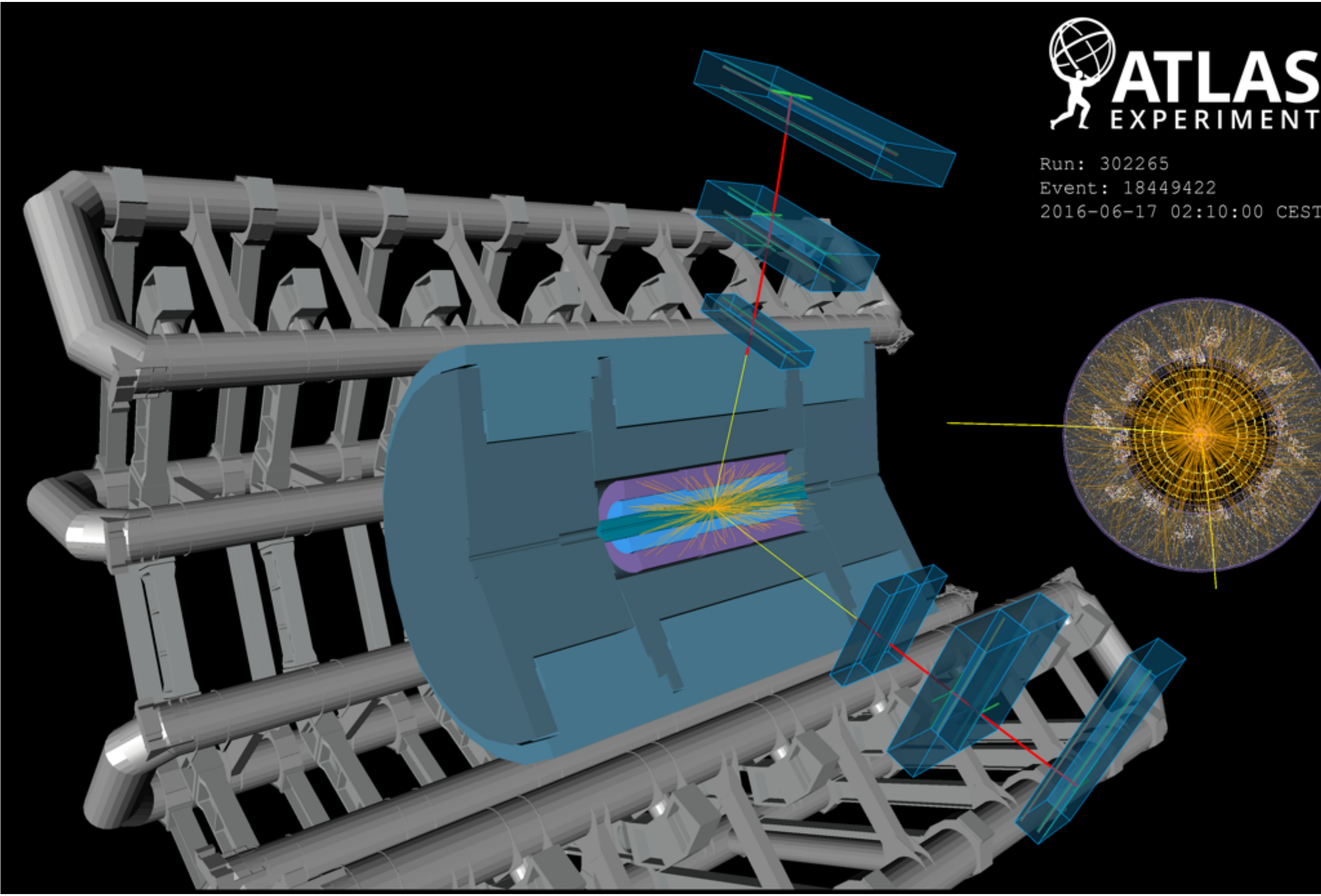
Opposite sign muon pair

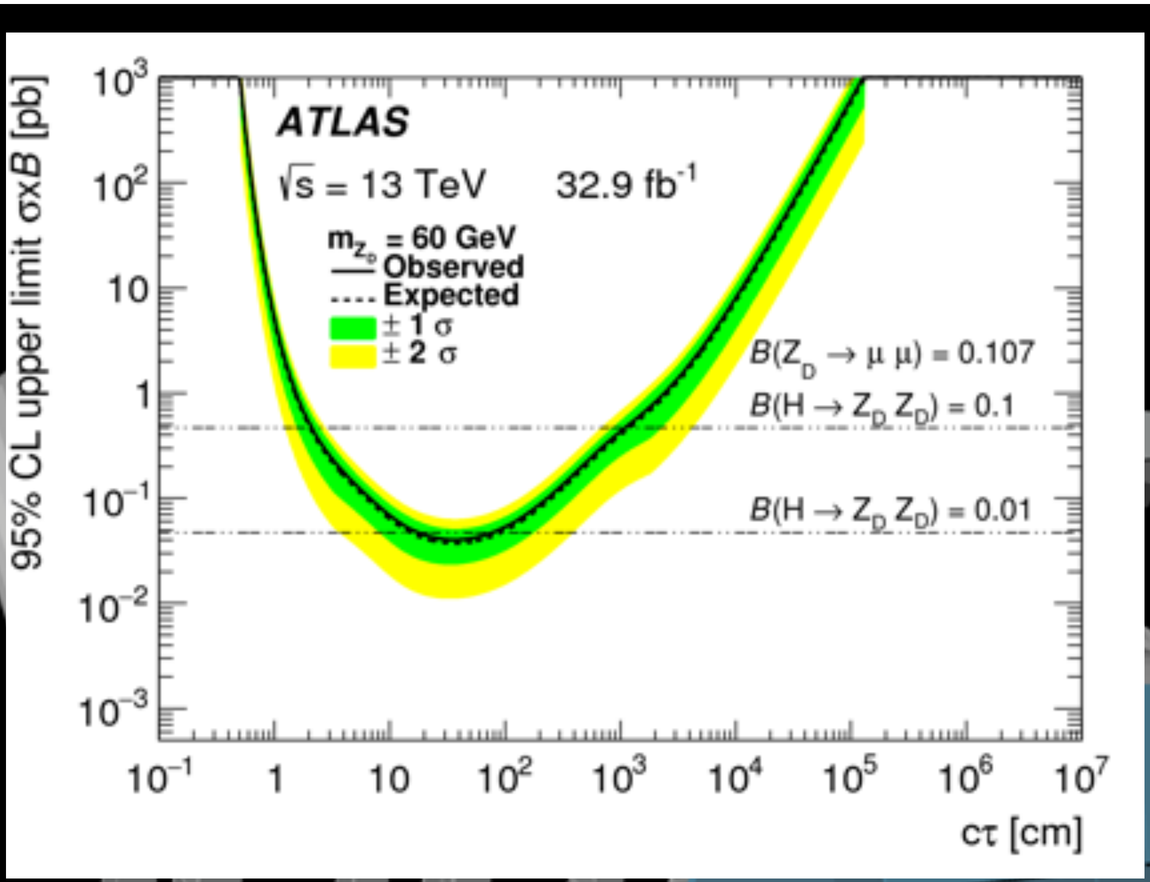


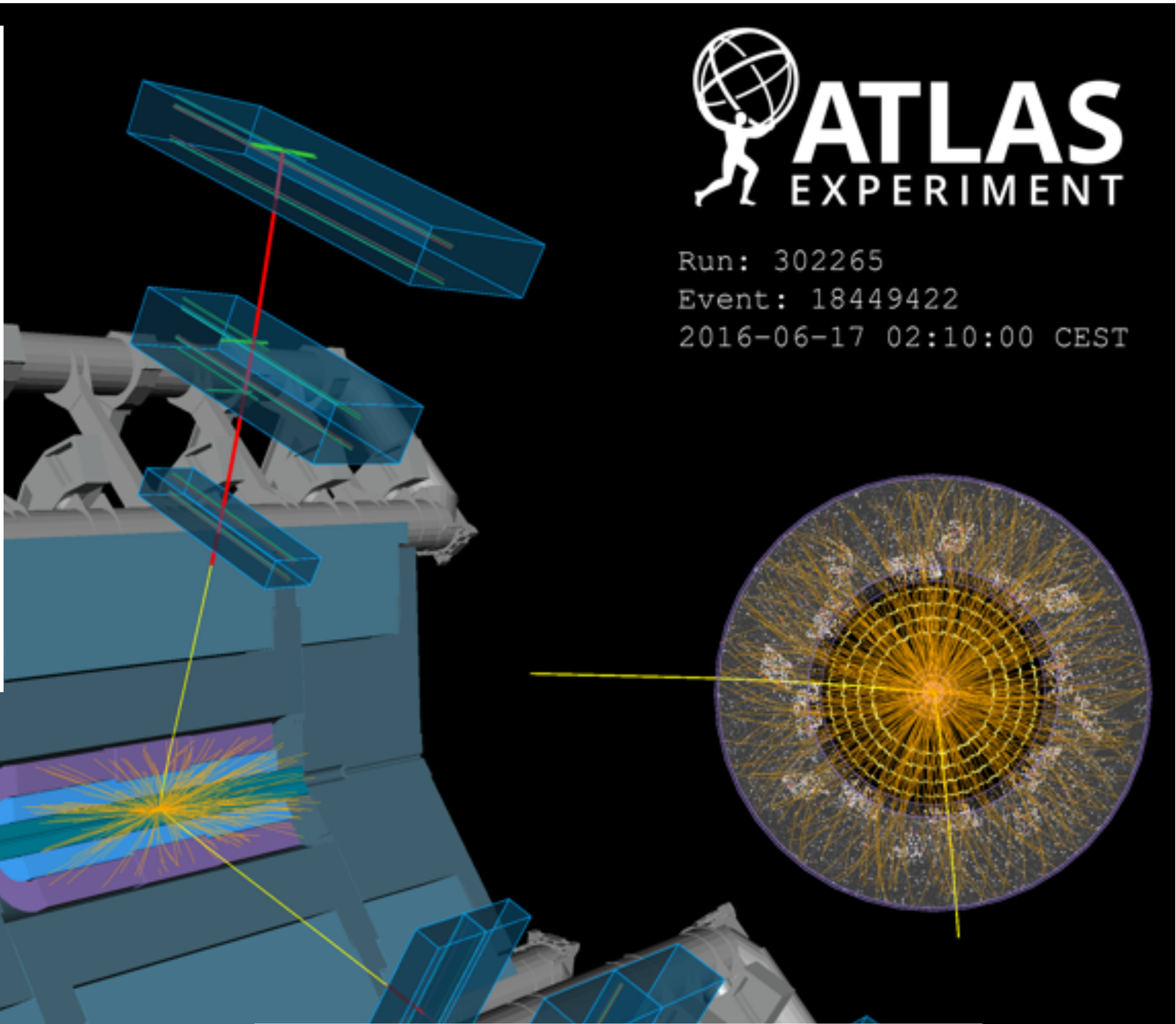
efficiency of finding the vertex would improve at low decay length and high masses by using tracking information earlier, at trigger

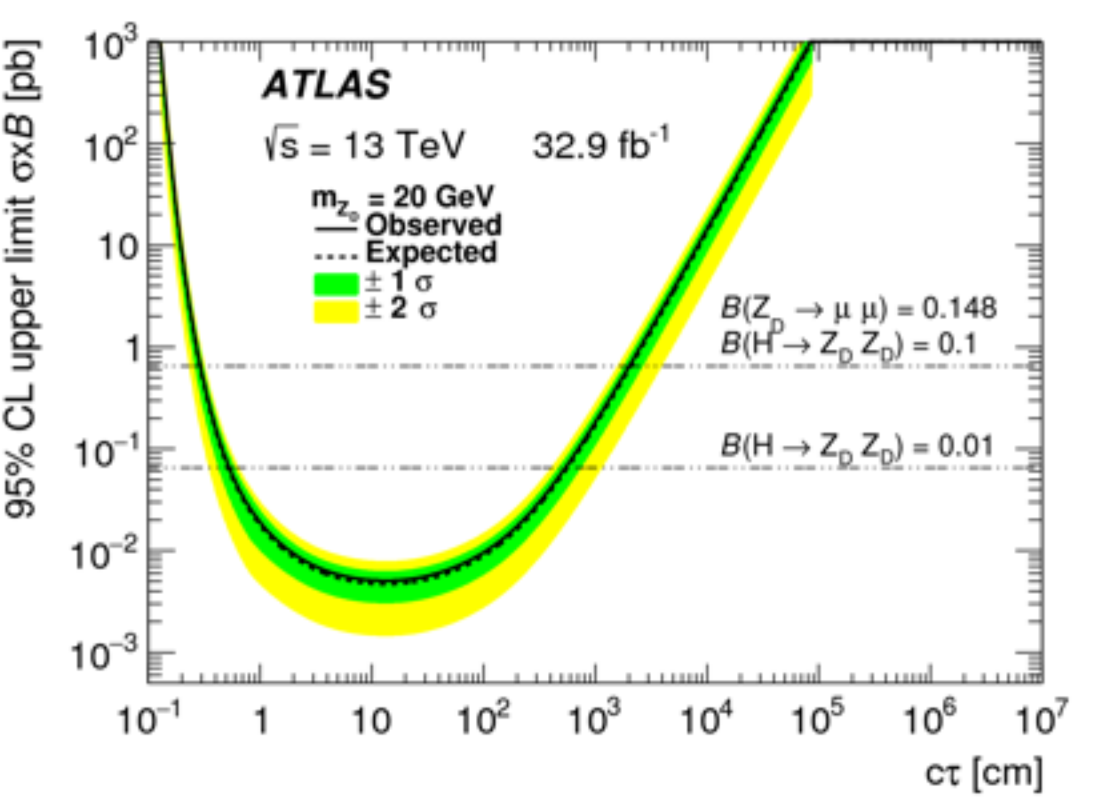
MET or (multi-)muon trigger. Extrapolate tracks from Muon Spectrometer to determine if consistent with a common vertex. Search region (1-400cm). Require large boost (pT/mass > 2) to suppress DY/Z+jets

Other backgrounds: cosmic μs, beam-induced background, π/K decays


ATLAS EXPERIMENT
Run: 302265
Event: 18449422
2016-06-17 02:10:00 CEST







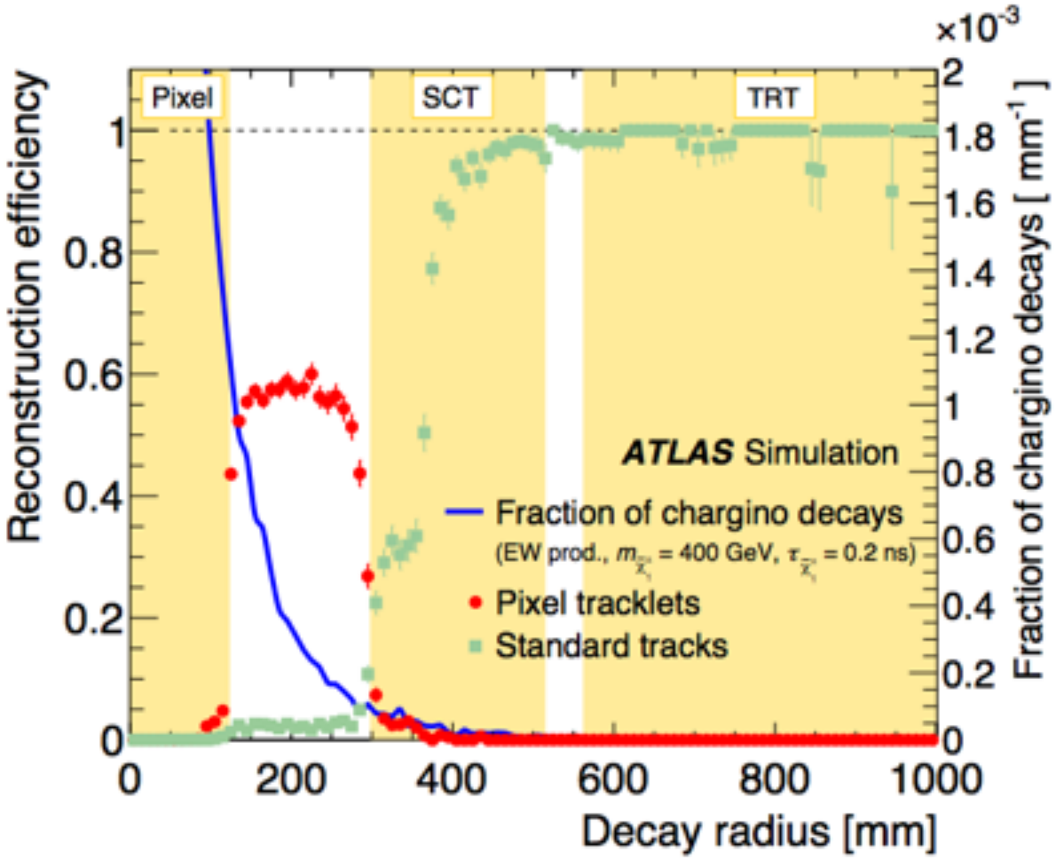
Yield	SR_{low}	SR_{high}
$N^{\text{non-prompt}}$	13.6 ± 4.9	$0.0^{+1.4}_{-0.0}$
N^{prompt}	0.1 ± 0.2	0.50 ± 0.07
N^{bkgd}	13.8 ± 4.9	$0.50^{+1.42}_{-0.07}$
N^{obs}	15	2

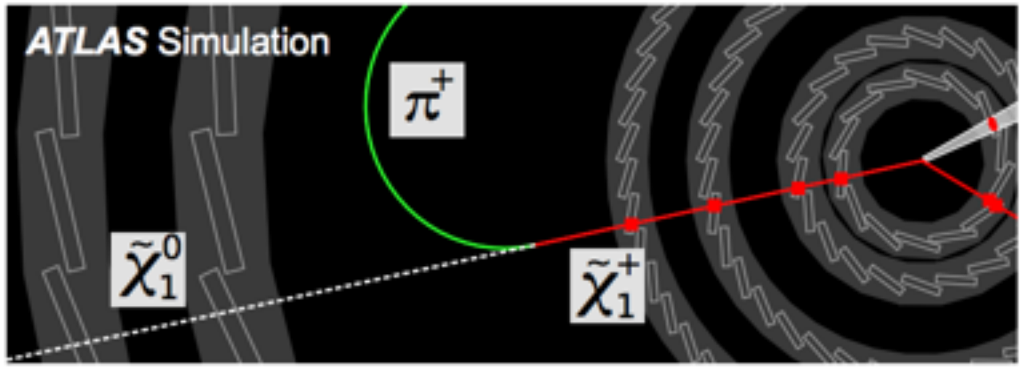
SRlow = mass(μμ)<60 GeV

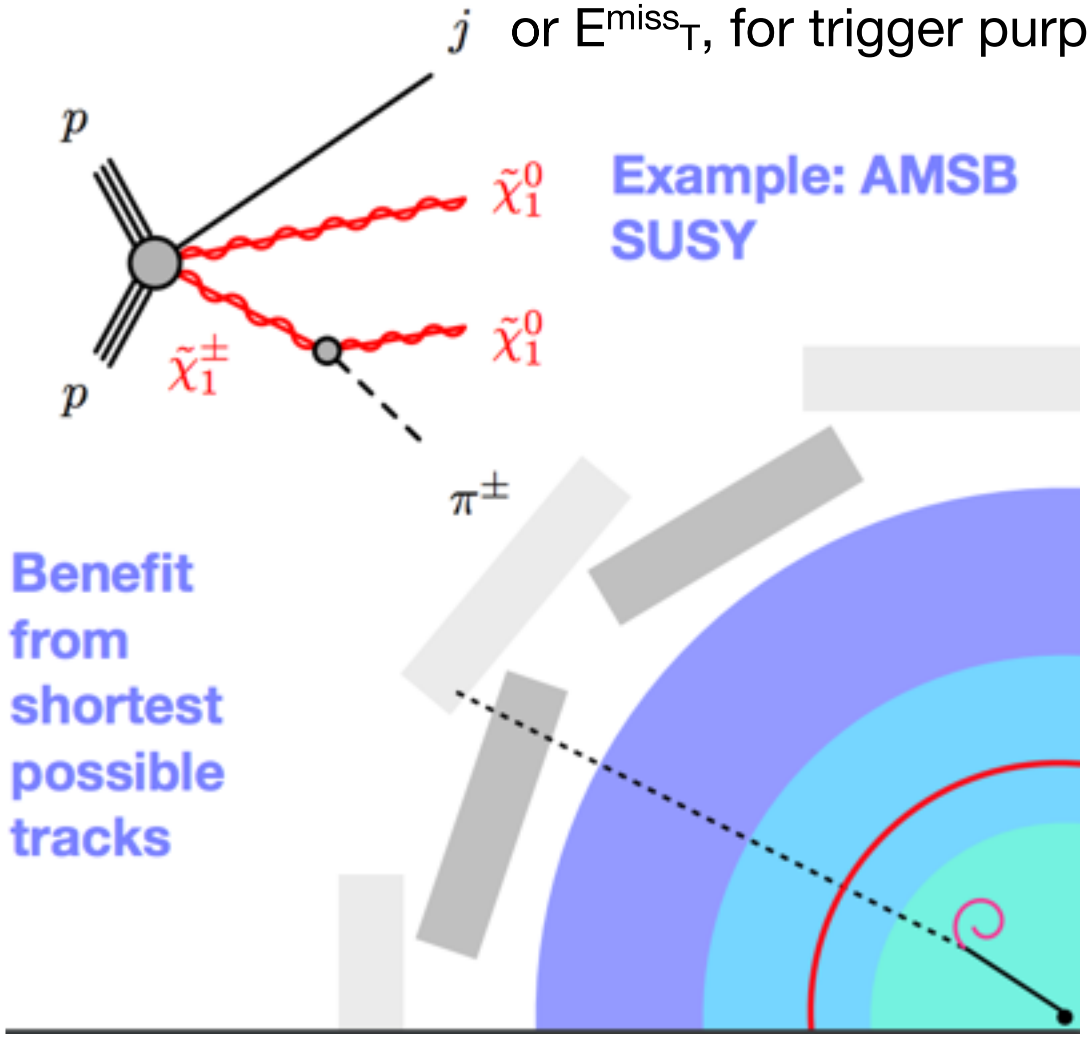
Disappearing tracks

Charged particle decaying to invisible particle of nearly degenerate mass gains long lifetime from small Δm. SM particle (π) too soft to reconstruct. Compressed scenarios.

request of E^{miss}_T or high-pT jet from initial state radiation, first of all to pass the trigger.
Having high pT track info instead, or seeing the kinked pion, early at trigger could increase efficiency for this (or other) compressed scenarios





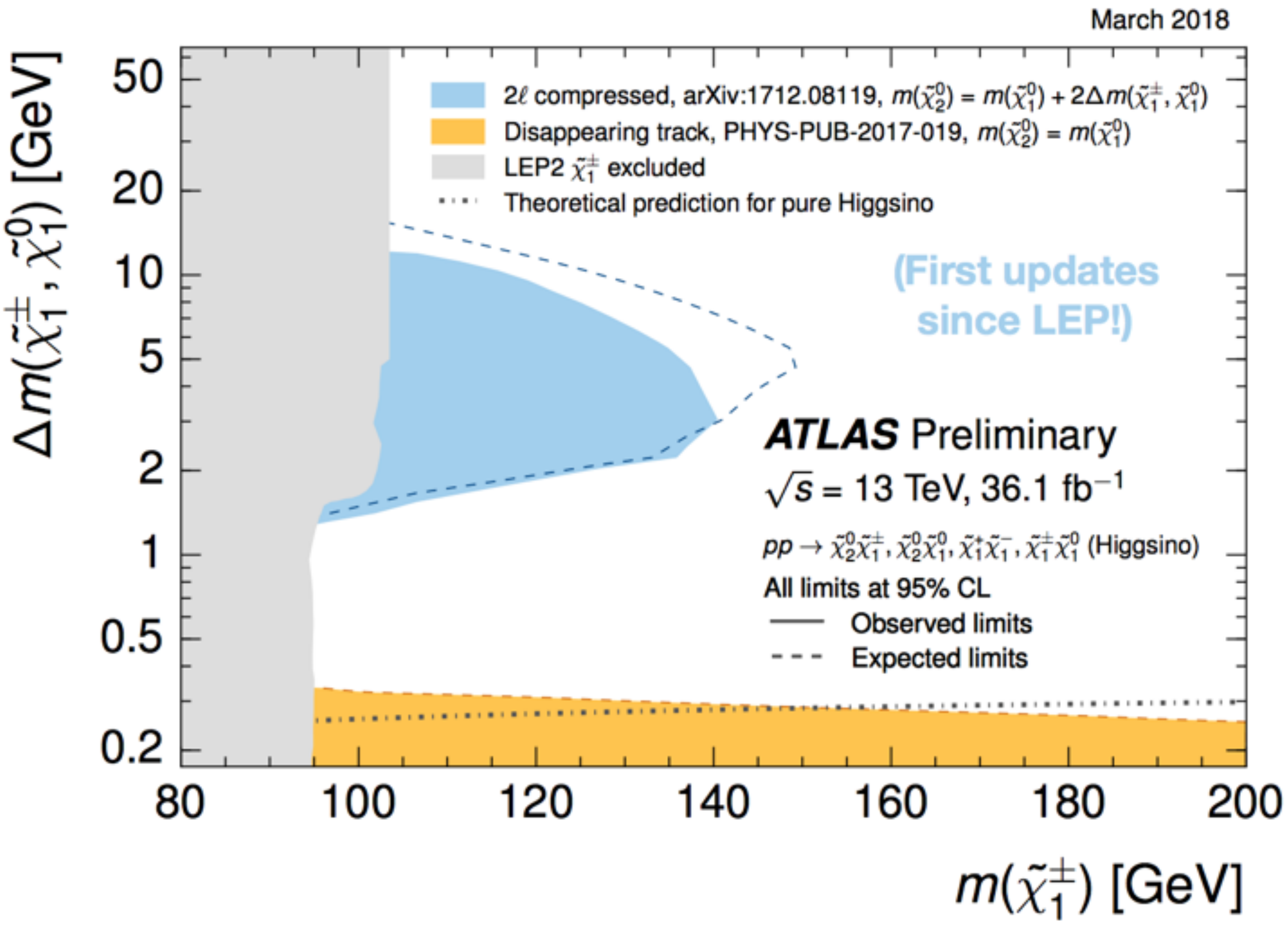


or E^{miss}_T, for trigger purpose

Example: AMSB SUSY

Benefit from shortest possible tracks

Disappearing tracks

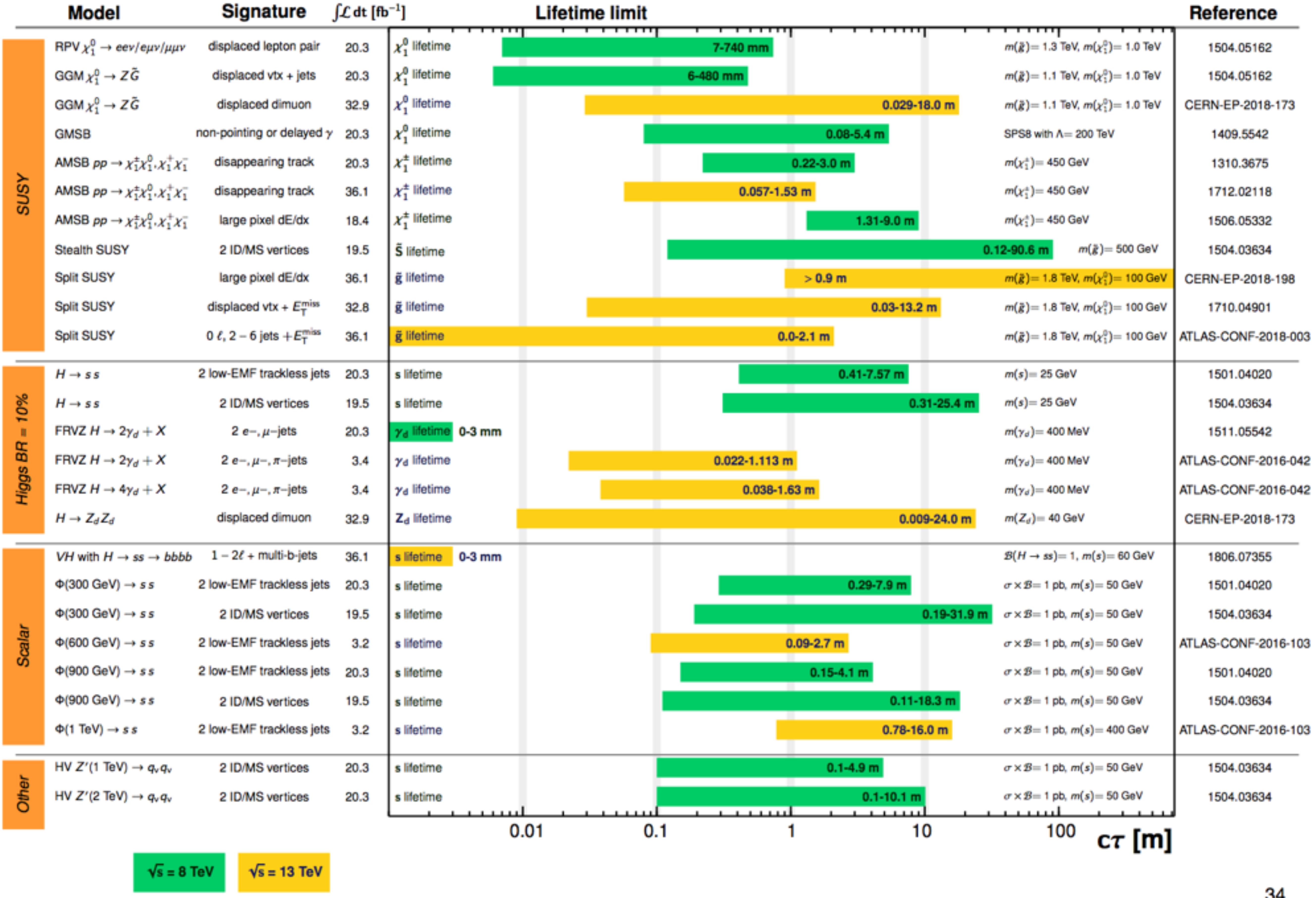


ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 36.1)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV



	Model	Signature	$\int \mathcal{L}\, dt\ [\text{fb}^{-1}]$	Lifetime limit			Reference
SUSY	RPV $\chi_1^0 \rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime	🟩 7-740 mm	$m(\tilde{g})$ = 1.3 TeV, $m(\chi_1^0)$ = 1.0 TeV	1504.05162
	GGM $\chi_1^0 \rightarrow Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime	🟩 6-480 mm	$m(\tilde{g})$ = 1.1 TeV, $m(\chi_1^0)$ = 1.0 TeV	1504.05162
	GGM $\chi_1^0 \rightarrow Z\tilde{G}$	displaced dimuon	32.9	χ_1^0 lifetime	🟨 0.029-18.0 m	$m(\tilde{g})$ = 1.1 TeV, $m(\chi_1^0)$ = 1.0 TeV	CERN-EP-2018-173
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	🟩 0.08-5.4 m	SPS8 with Λ = 200 TeV	1409.5542
	AMSB $pp \rightarrow \chi_1^{\pm}\chi_1^0, \chi_1^{+}\chi_1^{-}$	disappearing track	20.3	$\chi_1^{\pm}$ lifetime	🟩 0.22-3.0 m	$m(\chi_1^{\pm})$ = 450 GeV	1310.3675
	AMSB $pp \rightarrow \chi_1^{\pm}\chi_1^0, \chi_1^{+}\chi_1^{-}$	disappearing track	36.1	$\chi_1^{\pm}$ lifetime	🟨 0.057-1.53 m	$m(\chi_1^{\pm})$ = 450 GeV	1712.02118
	AMSB $pp \rightarrow \chi_1^{\pm}\chi_1^0, \chi_1^{+}\chi_1^{-}$	large pixel dE/dx	18.4	$\chi_1^{\pm}$ lifetime	🟩 1.31-9.0 m	$m(\chi_1^{\pm})$ = 450 GeV	1506.05332
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime	🟩 0.12-90.6 m	$m(\tilde{g})$ = 500 GeV	1504.03634
	Split SUSY	large pixel dE/dx	36.1	$\tilde{g}$ lifetime	🟨 > 0.9 m	$m(\tilde{g})$ = 1.8 TeV, $m(\chi_1^0)$ = 100 GeV	CERN-EP-2018-198
	Split SUSY	displaced vtx + E_T^{miss}	32.8	$\tilde{g}$ lifetime	🟨 0.03-13.2 m	$m(\tilde{g})$ = 1.8 TeV, $m(\chi_1^0)$ = 100 GeV	1710.04901
	Split SUSY	$0\ \ell, 2-6$ jets $+E_T^{\text{miss}}$	36.1	$\tilde{g}$ lifetime	🟨 0.0-2.1 m	$m(\tilde{g})$ = 1.8 TeV, $m(\chi_1^0)$ = 100 GeV	ATLAS-CONF-2018-003
Higgs BR = 10%	$H \rightarrow s\,s$	2 low-EMF trackless jets	20.3	s lifetime	🟩 0.41-7.57 m	$m(s)$ = 25 GeV	1501.04020
	$H \rightarrow s\,s$	2 ID/MS vertices	19.5	s lifetime	🟩 0.31-25.4 m	$m(s)$ = 25 GeV	1504.03634
	FRVZ $H \rightarrow 2\gamma_d + X$	2 $e-, \mu-$jets	20.3	γ_d lifetime	🟩 0-3 mm	$m(\gamma_d)$ = 400 MeV	1511.05542
	FRVZ $H \rightarrow 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	🟨 0.022-1.113 m	$m(\gamma_d)$ = 400 MeV	ATLAS-CONF-2016-042
	FRVZ $H \rightarrow 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	3.4	γ_d lifetime	🟨 0.038-1.63 m	$m(\gamma_d)$ = 400 MeV	ATLAS-CONF-2016-042
	$H \rightarrow Z_d Z_d$	displaced dimuon	32.9	Z_d lifetime	🟨 0.009-24.0 m	$m(Z_d)$ = 40 GeV	CERN-EP-2018-173
Scalar	VH with $H \rightarrow ss \rightarrow bbbb$	$1-2\ell$ + multi-b-jets	36.1	s lifetime	🟨 0-3 mm	$\mathcal{B}(H \rightarrow ss)$ = 1, $m(s)$ = 60 GeV	1806.07355
	Φ(300 GeV) $\rightarrow s\,s$	2 low-EMF trackless jets	20.3	s lifetime	🟩 0.29-7.9 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 50 GeV	1501.04020
	Φ(300 GeV) $\rightarrow s\,s$	2 ID/MS vertices	19.5	s lifetime	🟩 0.19-31.9 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 50 GeV	1504.03634
	Φ(600 GeV) $\rightarrow s\,s$	2 low-EMF trackless jets	3.2	s lifetime	🟨 0.09-2.7 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 50 GeV	ATLAS-CONF-2016-103
	Φ(900 GeV) $\rightarrow s\,s$	2 low-EMF trackless jets	20.3	s lifetime	🟩 0.15-4.1 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 50 GeV	1501.04020
	Φ(900 GeV) $\rightarrow s\,s$	2 ID/MS vertices	19.5	s lifetime	🟩 0.11-18.3 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 50 GeV	1504.03634
	Φ(1 TeV) $\rightarrow s\,s$	2 low-EMF trackless jets	3.2	s lifetime	🟨 0.78-16.0 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 400 GeV	ATLAS-CONF-2016-103
Other	HV Z'(1 TeV) $\rightarrow q_v q_v$	2 ID/MS vertices	20.3	s lifetime	🟩 0.1-4.9 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 50 GeV	1504.03634
	HV Z'(2 TeV) $\rightarrow q_v q_v$	2 ID/MS vertices	20.3	s lifetime	🟩 0.1-10.1 m	$\sigma \times \mathcal{B}$ = 1 pb, $m(s)$ = 50 GeV	1504.03634

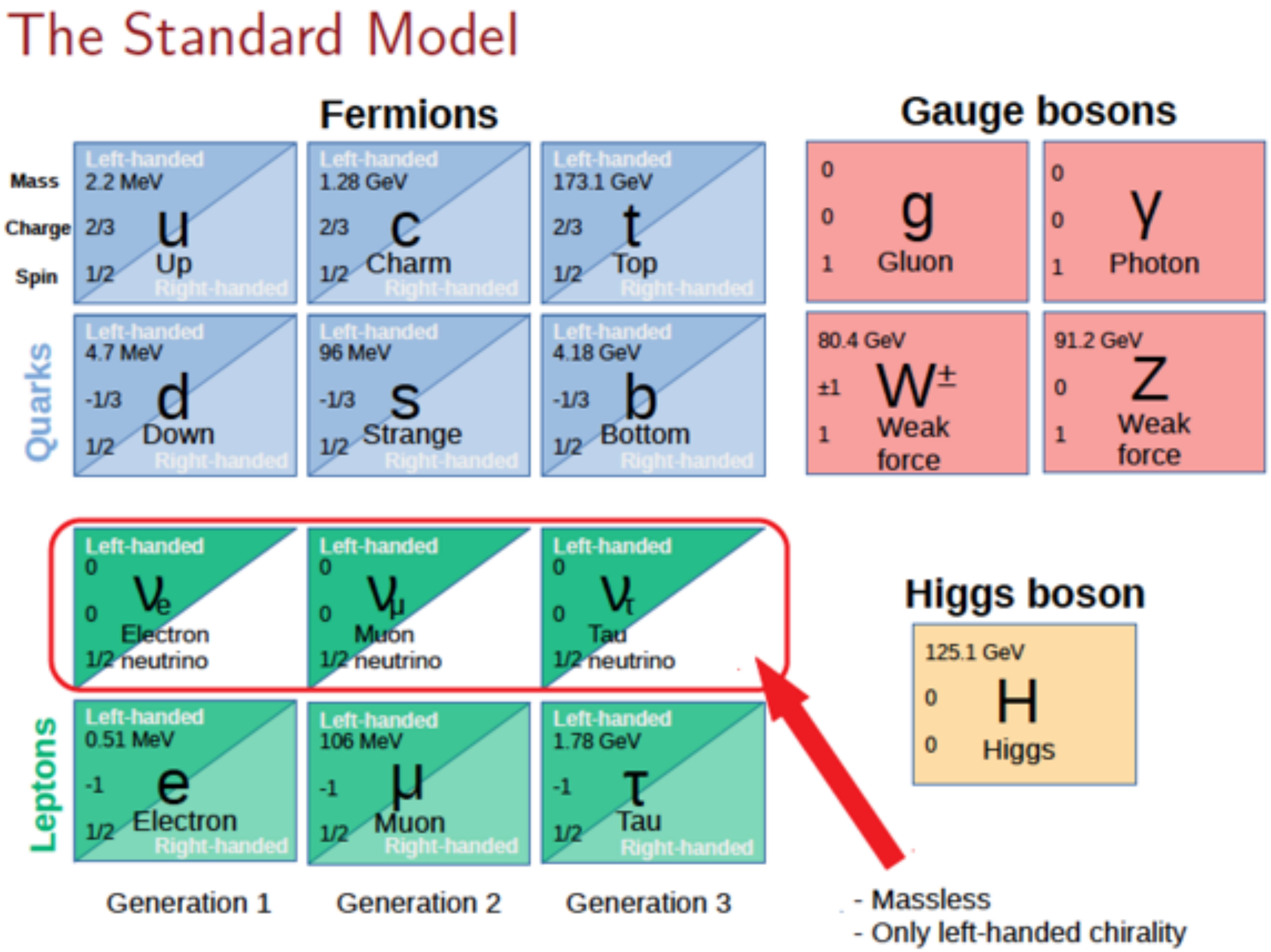
🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available lifetime limits on new states is shown.

$(\gamma\beta = 1)$

- neutrino mass/mixing : Heavy neutral Lepton

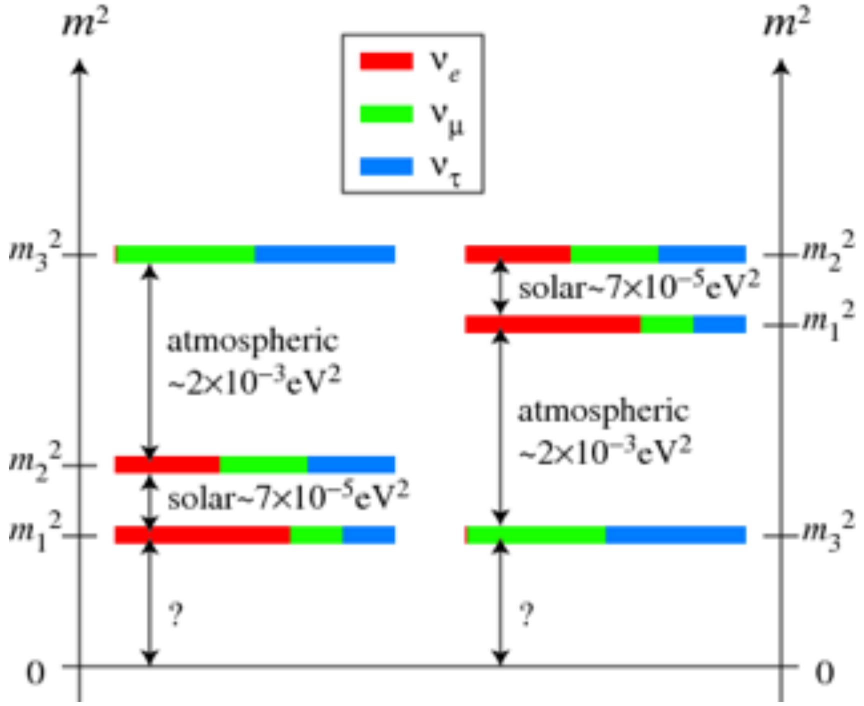
Neutrinos in the SM



- Massless
- Only left-handed chirality

But !
neutrinos have mass

this is per-se
a very striking
sign of
physics we cannot
explain with the SM



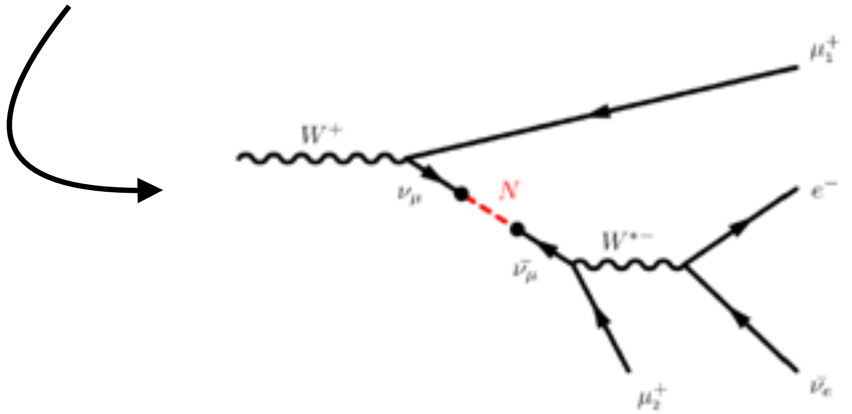
How do neutrinos get mass

Add three heavy right-handed Majorana neutrinos to the SM.

Neutrino
Minimal Standard Model
https://arxiv.org/pdf/0901.0011.pdf

Properties of the right-handed neutrinos:

- Produced through mixing with the active neutrinos.
- One "dark matter candidate". M_1
- Two mass-degenerate right-handed neutrinos. M_2
  Can be produced and searched for at the LHC!



mixing parameters with active neutrinos

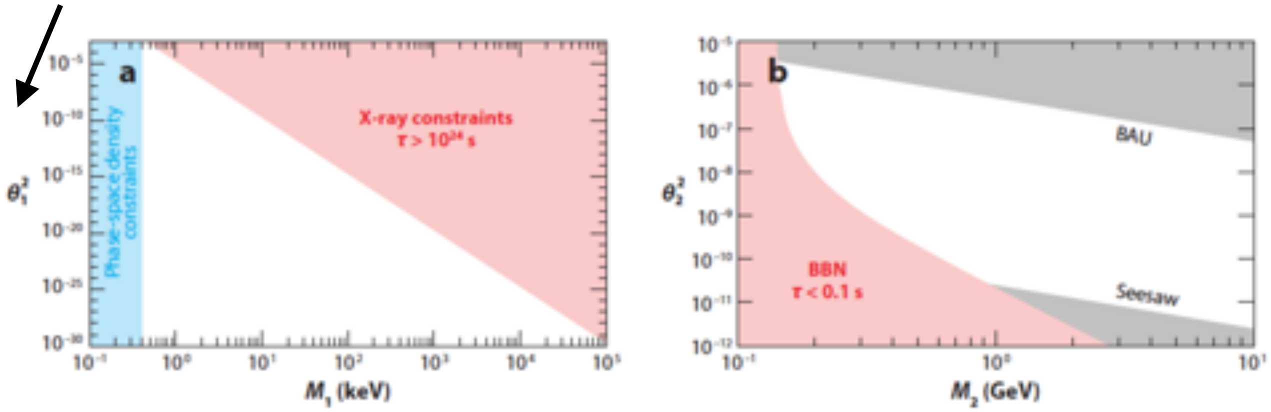
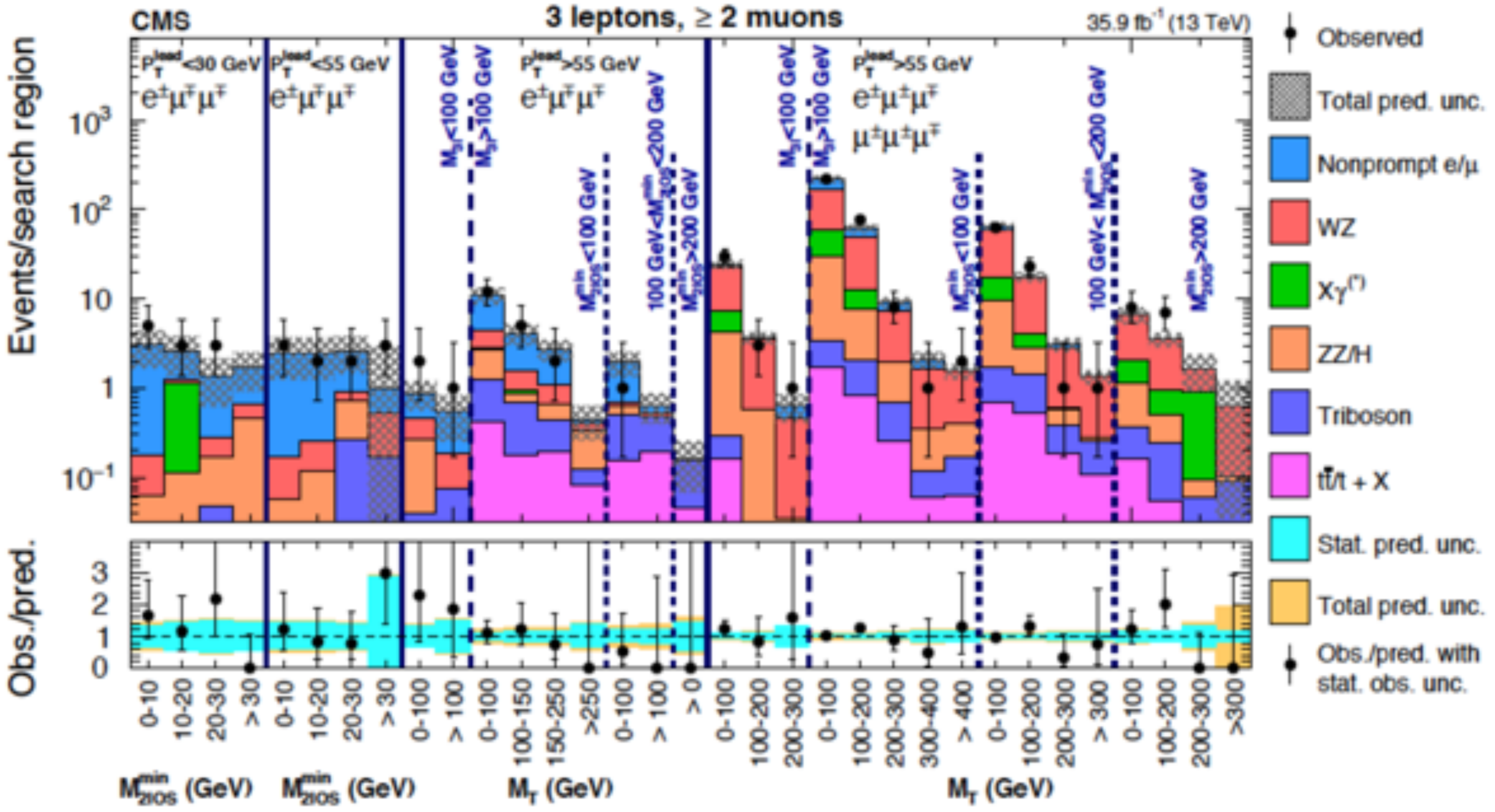


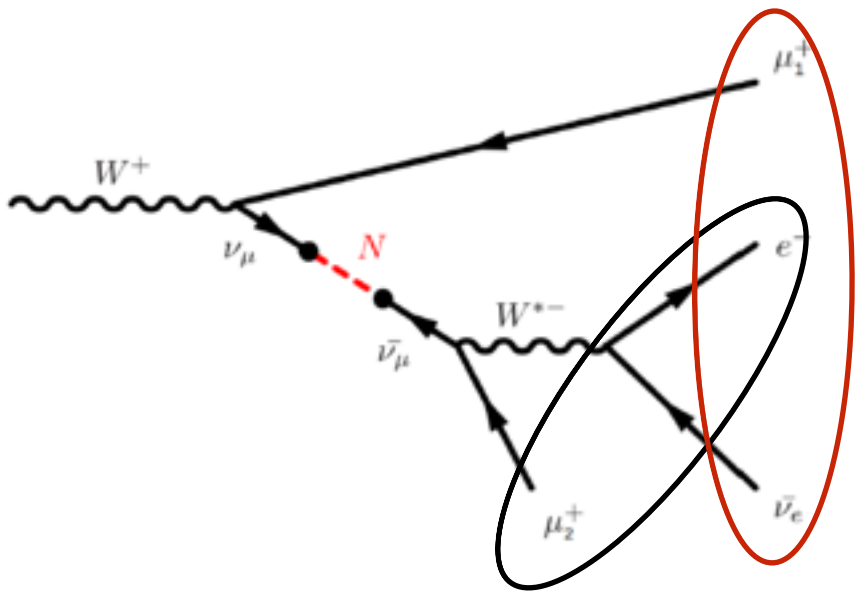
Figure 1
Constraints on the masses and mixing angles of the dark matter sterile neutrino N_1 (*a*) and of two heavier sterile neutrinos $N_{2,3}$ (*b*). These constraints come from astrophysics, cosmology, and neutrino oscillation experiments. Abbreviations: BAU, baryon asymmetry of the Universe; BBN, big bang nucleosynthesis.

Mass range is below the W mass

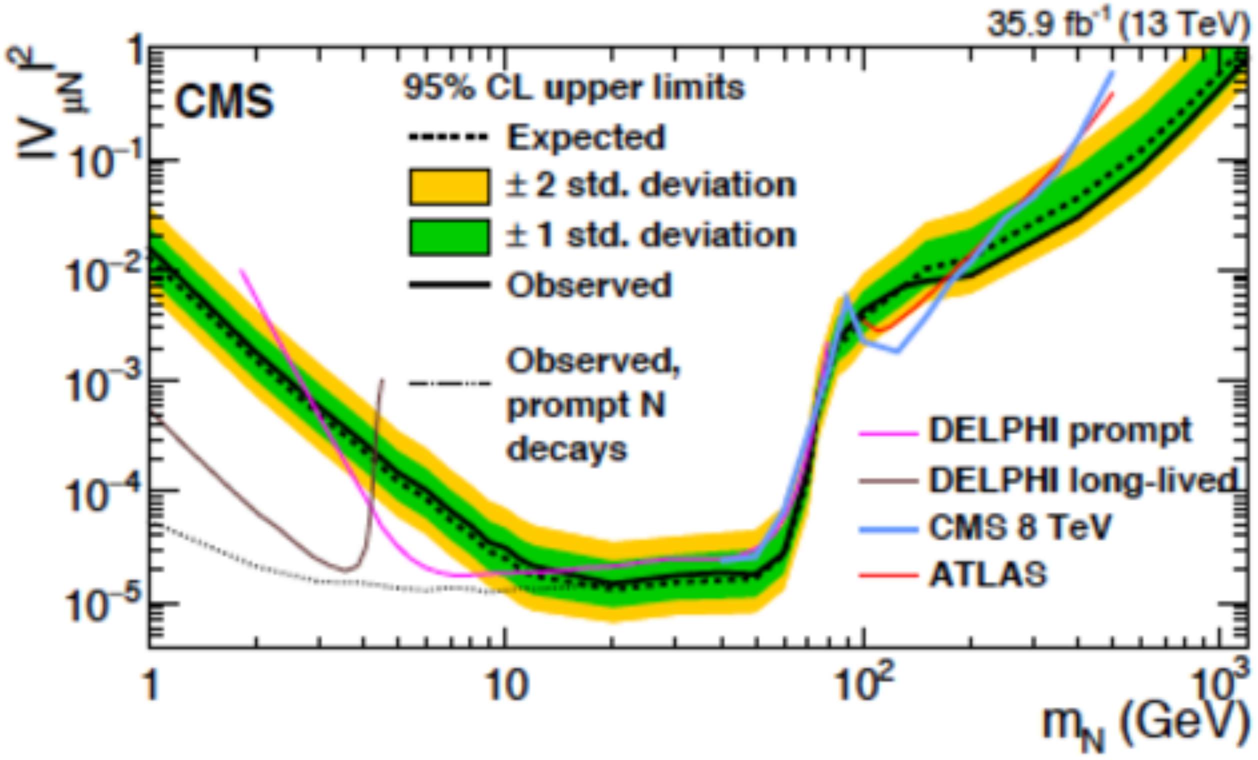
arXiv: 1802.02965

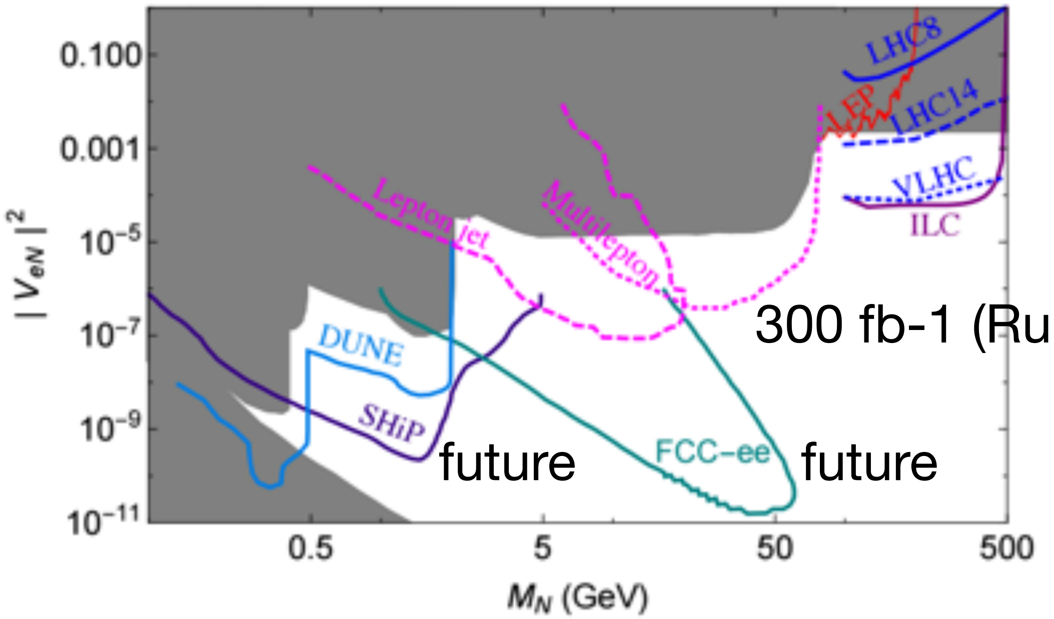


$M_T=\sqrt{2p^l_T E^{miss}_T(1-\cos\Delta\phi)}$



M^{min}_{2lOS}





300 fb-1 (Run-3)

future

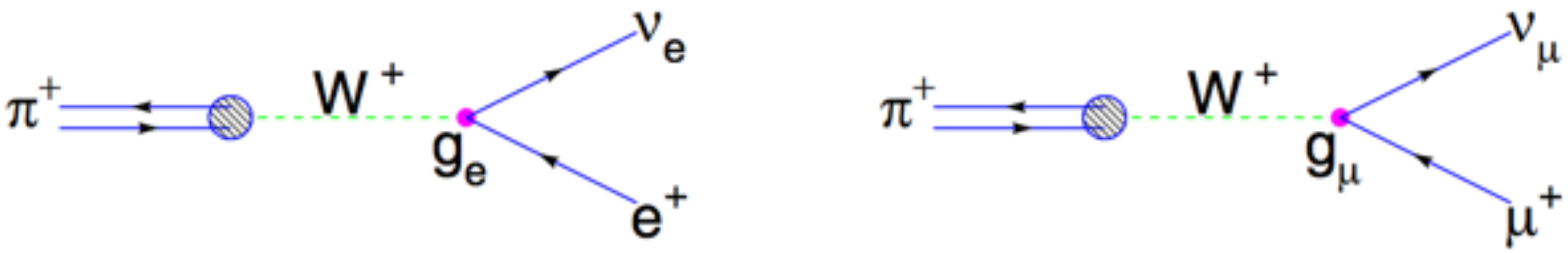
future

- B-physics

Lepton Flavour Universality

SM interactions do not differentiate between leptons of different flavor

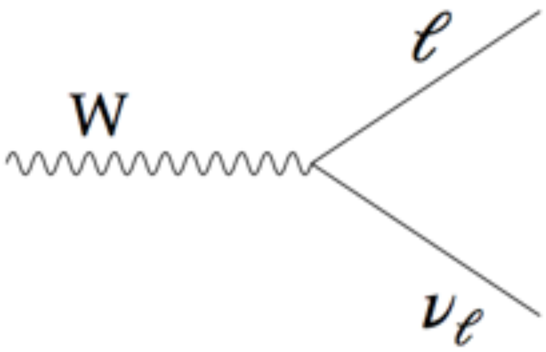
This is an assumption of the SM, no deviation observed



(from TRIUMF and PSI measurements)

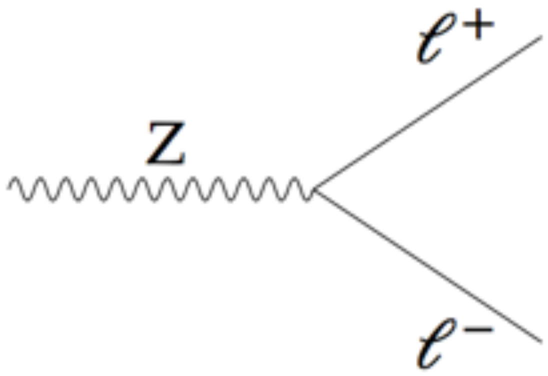
From PDG

$$\frac{g_\mu}{g_e} = 1.0023 \pm 0.0016$$



From PDG

$W^+ \to \ell \nu_\ell$	Fraction (Γi/Γ)
$e^+\nu$	$(10.71 \pm 0.16)\%$
$\mu^+\nu$	$(10.63 \pm 0.15)\%$
$\tau^+\nu$	$(11.38 \pm 0.21)\%$



From PDG

$Z \to \ell^+\ell^-$	Fraction (Γi/Γ)
e^+e^-	$(3.3632 \pm 0.0042)\%$
$\mu^+\mu^-$	$(3.3662 \pm 0.0066)\%$
$\tau^+\tau^-$	$(3.3696 \pm 0.0083)\%$

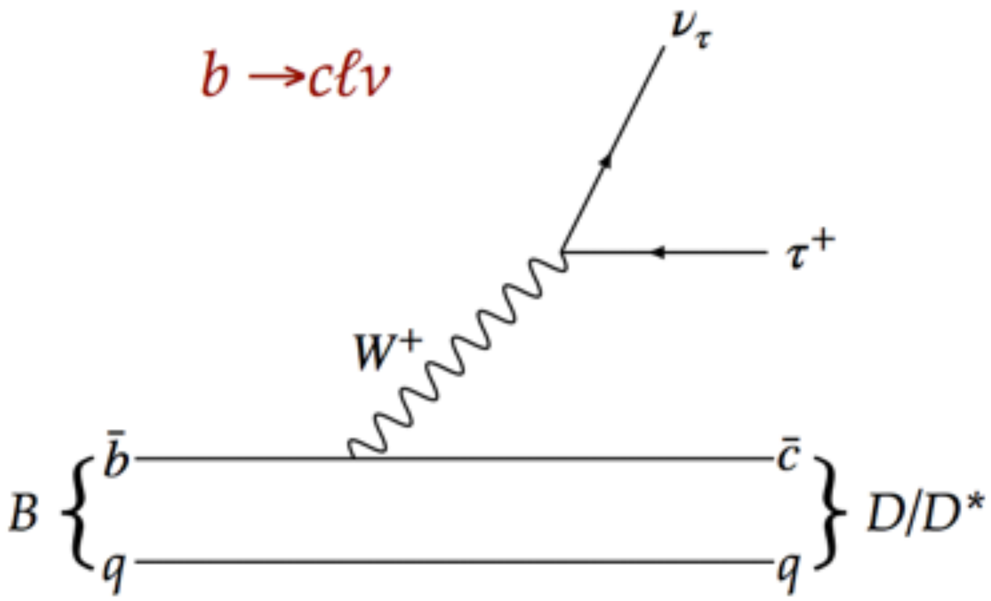
“Clean” B decays

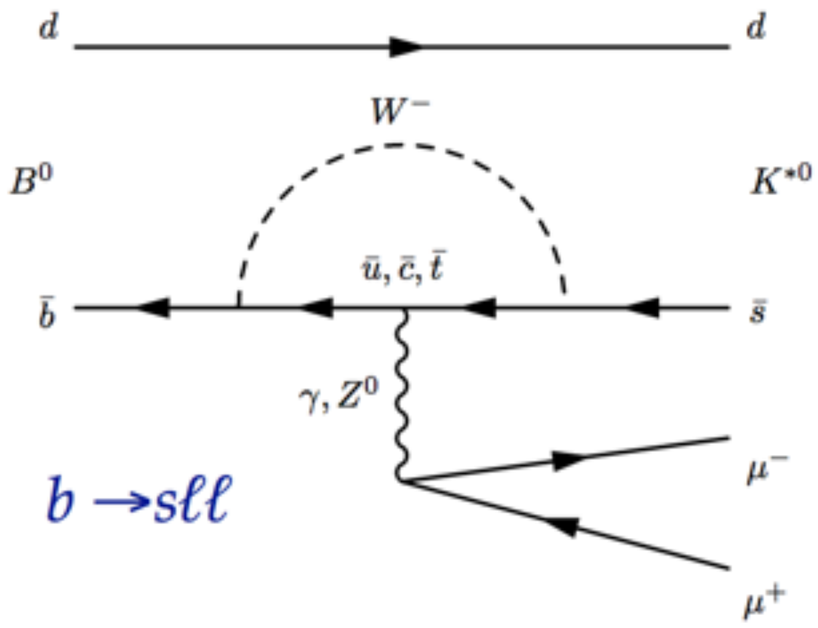
Charged current (Semileptonic decays, SL):

- Tree level, BR of few %
- strong and weak part factorise
  => clean SM predictions
- NP sensitivity up to ~ 1 TeV

Neutral currents (Rare decays, RD):

- FCNC processes → only at loop level → BR ~ $10^{-7} \div 10^{-6}$
- new particles can enhance SM-suppressed amplitudes
- NP sensitivity up to ~ 100 TeV





$$R(X) = \frac{BR(B \to X\tau\bar{\nu}_\tau)}{BR(B \to X\mu\bar{\nu}_\mu)}$$

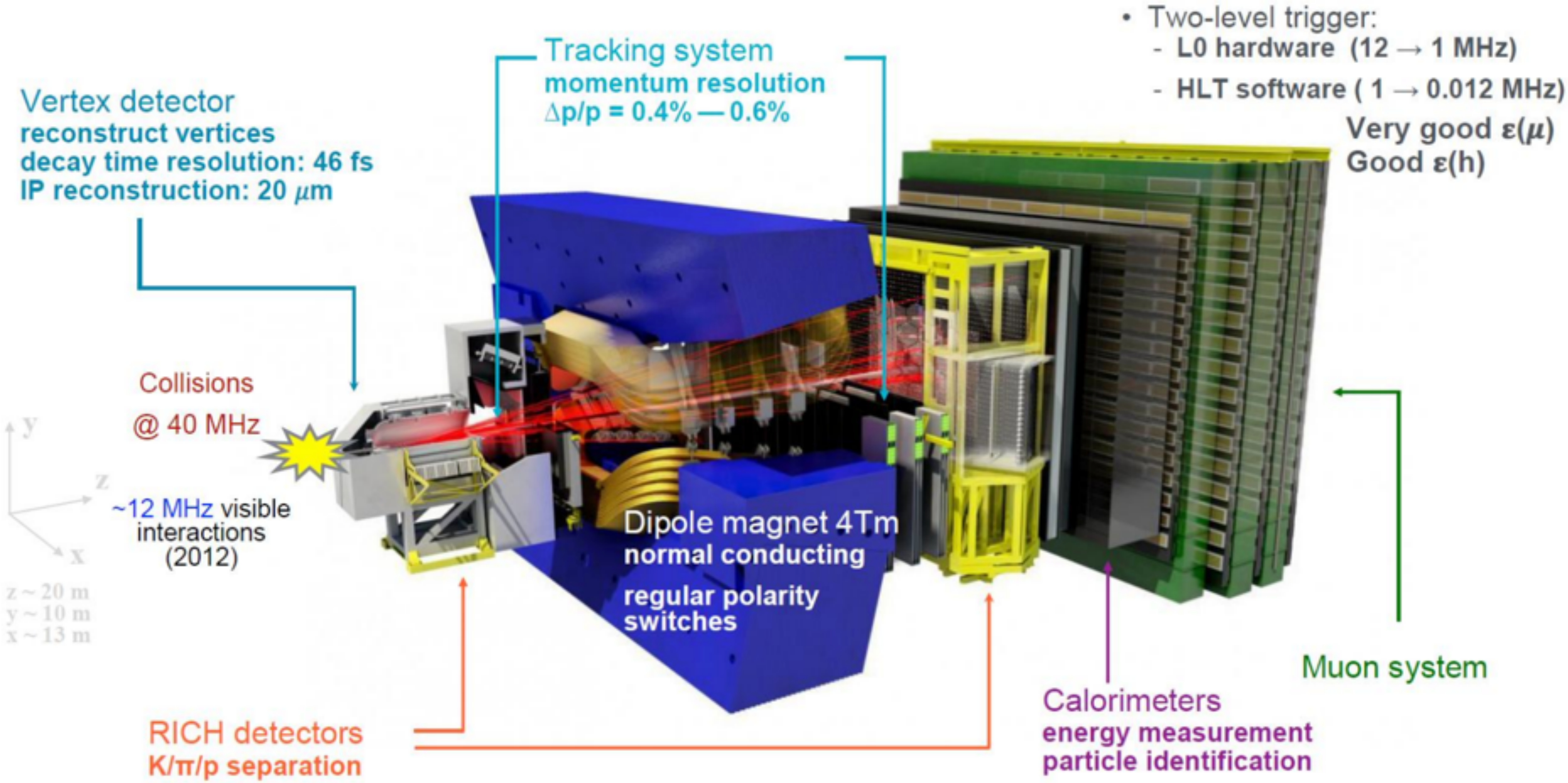
signal

normalization

$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to(e^+e^-))}$$

where: $X = D, D^*$ and: $\tau \to \mu\nu_\tau\bar{\nu}_\mu$ or: $\tau \to 3h\nu_\tau$

LHC-b



- Two-level trigger:
  - L0 hardware (12 → 1 MHz)
  - HLT software (1 → 0.012 MHz)

Vertex detector
reconstruct vertices
decay time resolution: 46 fs
IP reconstruction: 20 μm

Tracking system
momentum resolution
$\Delta p/p = 0.4\% — 0.6\%$

Very good $\varepsilon(\mu)$
Good $\varepsilon(h)$

Collisions
@ 40 MHz

~12 MHz visible
interactions
(2012)

Dipole magnet 4Tm
normal conducting

regular polarity
switches

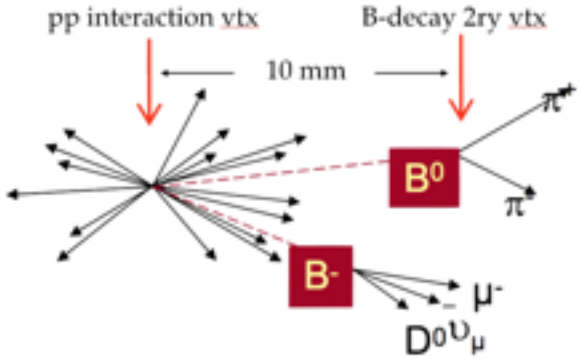
RICH detectors
K/π/p separation

Calorimeters
energy measurement
particle identification

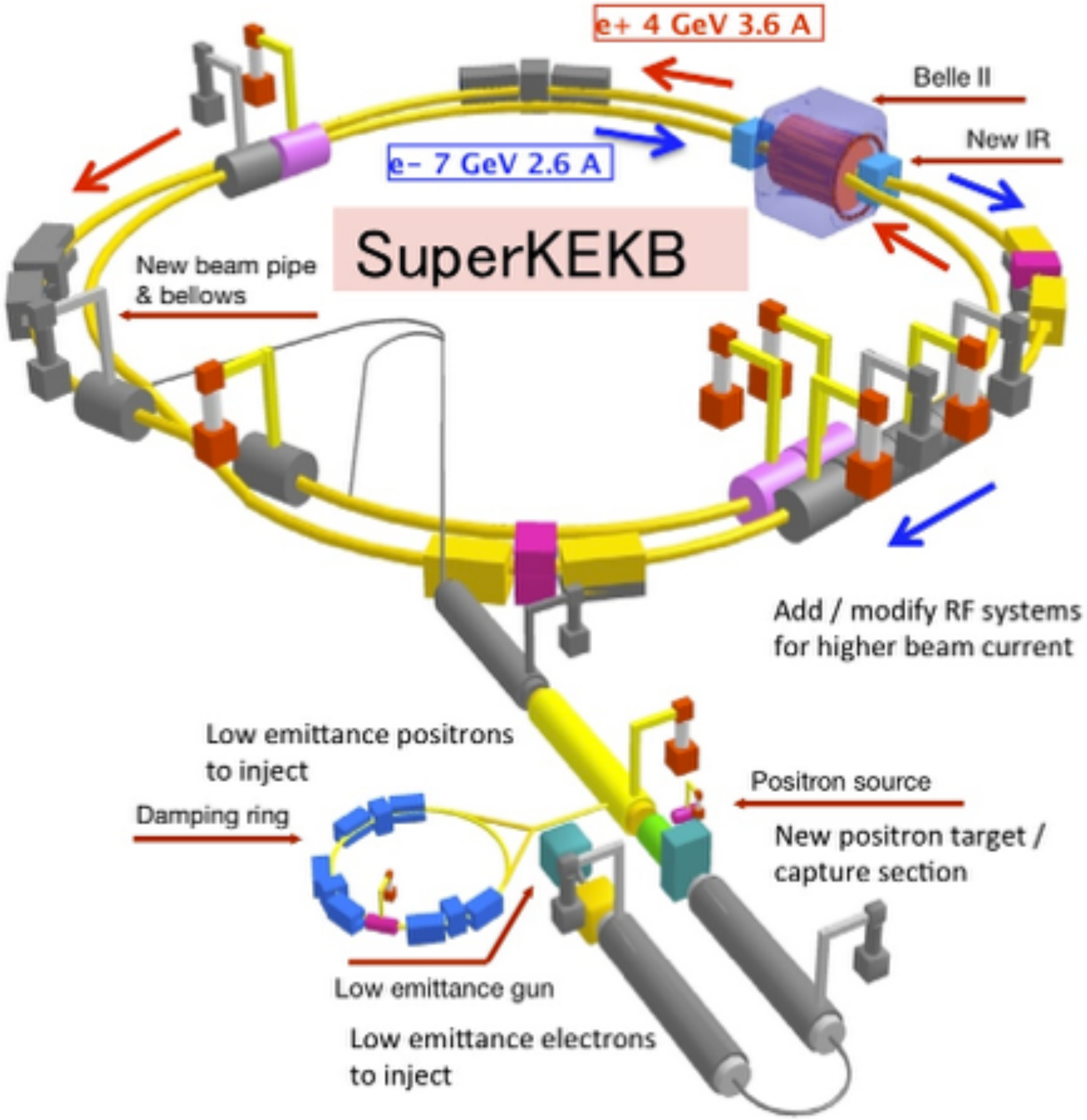
Muon system

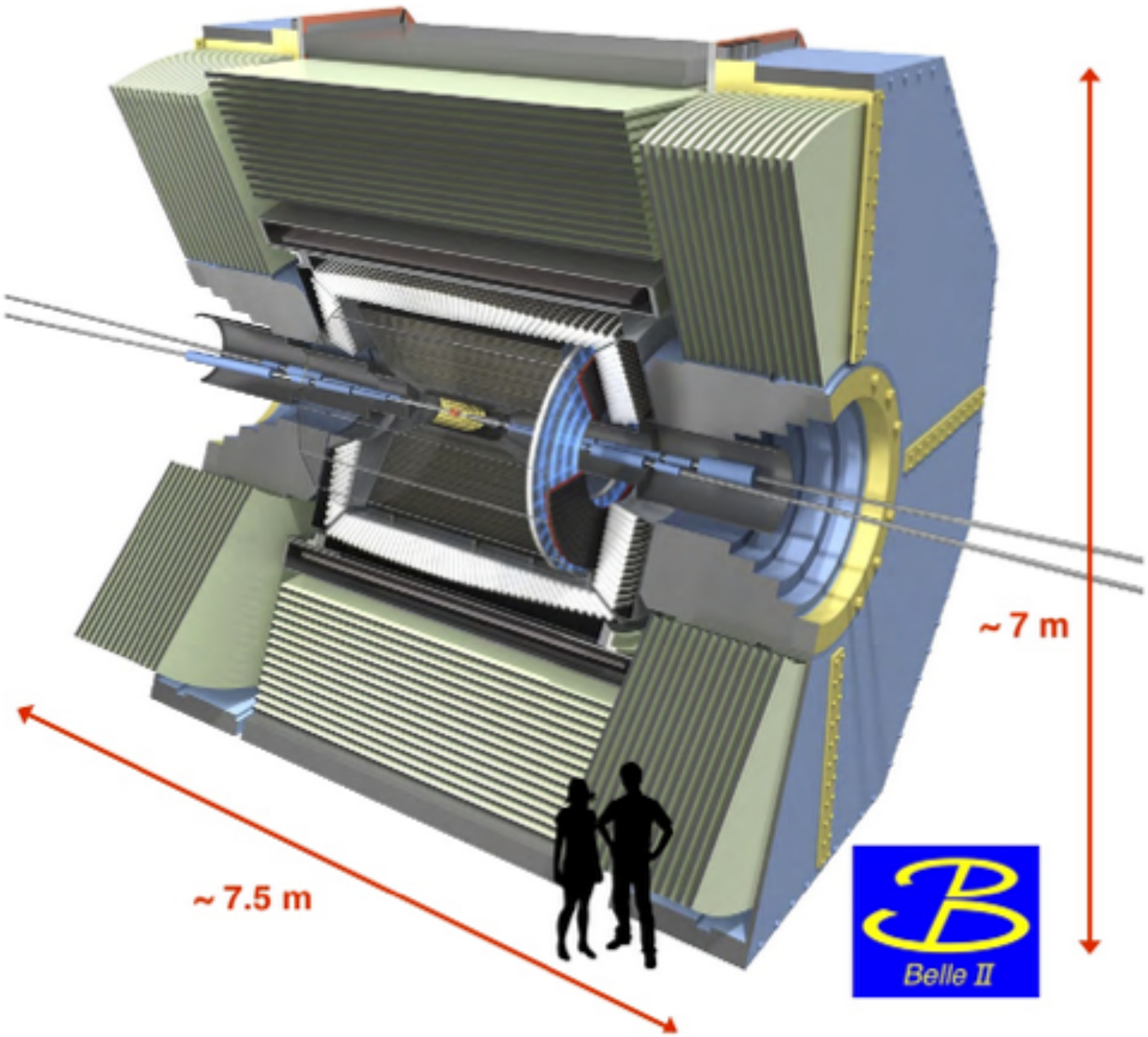
Unique features:

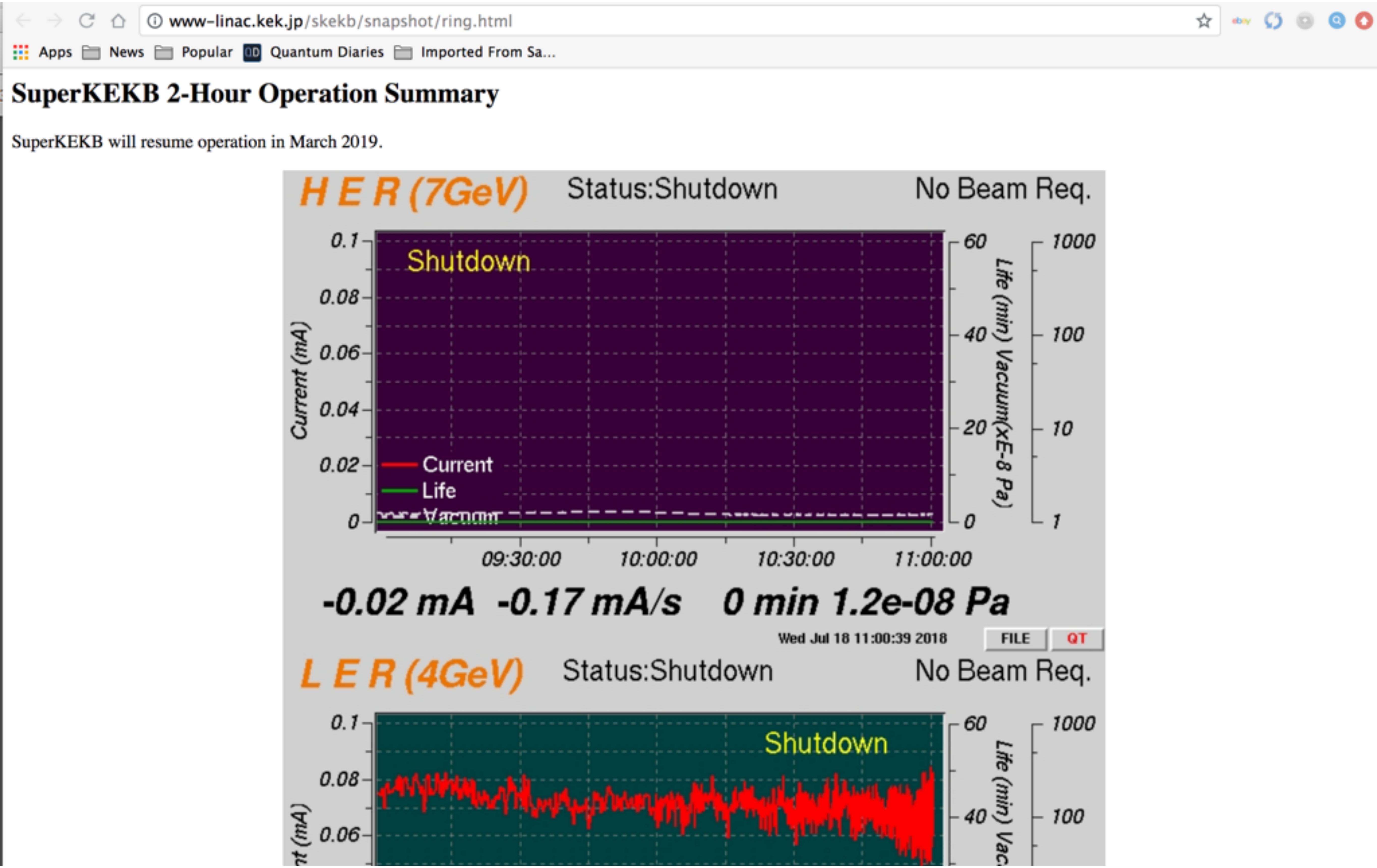
- Real time selection of collisions with beauty or charm content
- Exceptionally good resolution on particle time of flights
- Separation pions / kaons



The Present/Future







SuperKEKB 2-Hour Operation Summary

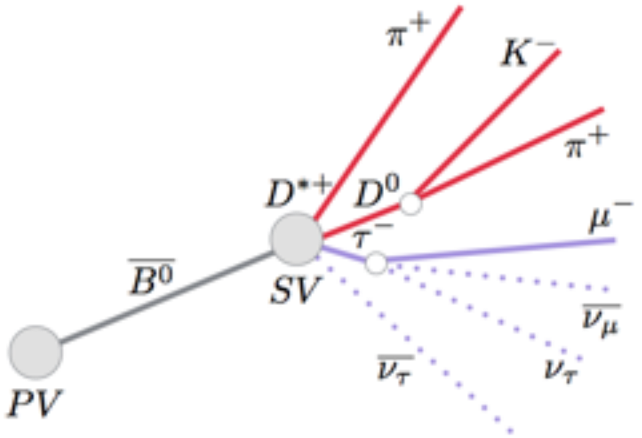
SuperKEKB will resume operation in March 2019.

PRL115(2015)111803
PRL 120, 171802 2018
PRD 97,072013 2018

R(D/D*)

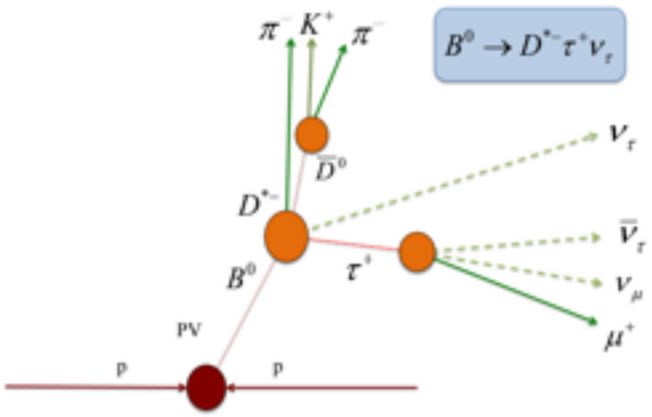
@ LHCb

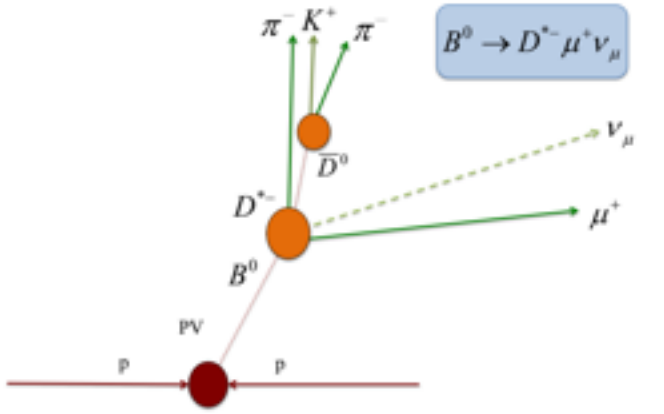
- Full reconstruction of both B’s, as in Babar/Belle (earlier e+e- B factories), impossible
- Compensate using large boost (flight information) and huge B production
- B flight direction given by PV and SV
- Approximated B momentum along the beam: $p_z = (m / m_{rec}) p_{rec,z}$



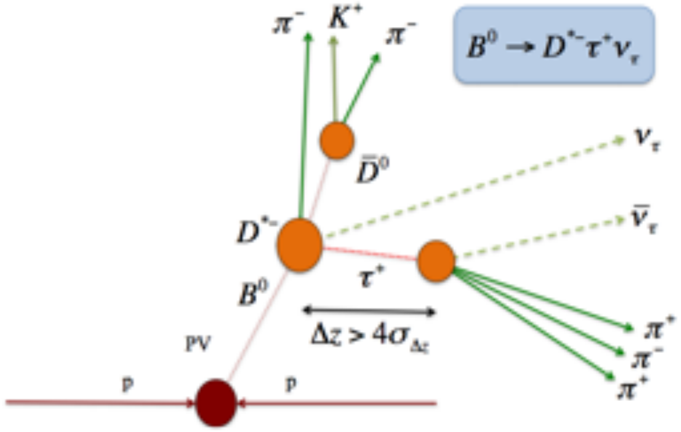
Separation of the two channels performed exploiting distinct kinematic distributions due to:

- μ-τ mass difference
- presence of extra neutrinos in signal channel





$$R(D^*) = \frac{BR(B \to D^*\tau\bar{\nu}_\tau)}{BR(B \to D^*\mu\bar{\nu}_\mu)} \qquad \text{where: } \tau \to \mu\bar{\nu}_\mu\nu_\tau$$



$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \qquad R(D^*) \equiv \mathcal{K}(D^*) \times \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

[~4% precision, BaBar, Belle, LHCb]
[~2% precision, HFLAV 2016]

PRL115(2015)111803
PRL 120, 171802 2018
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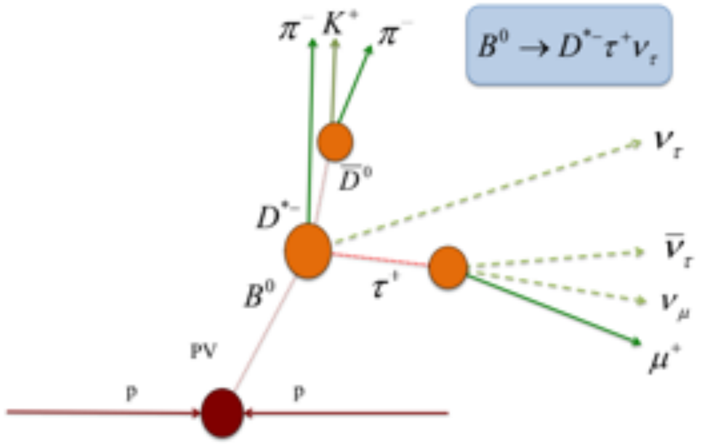

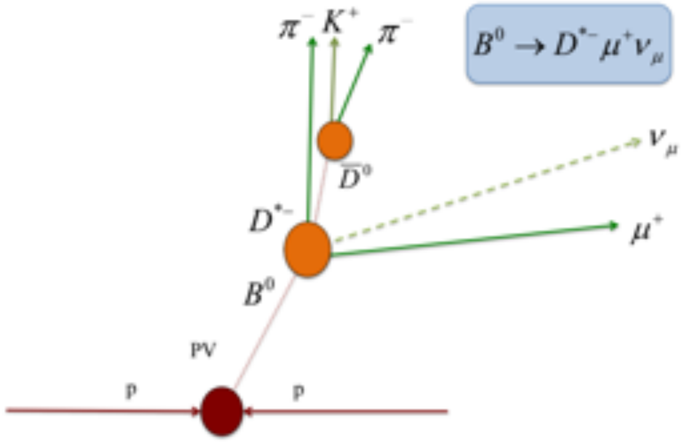

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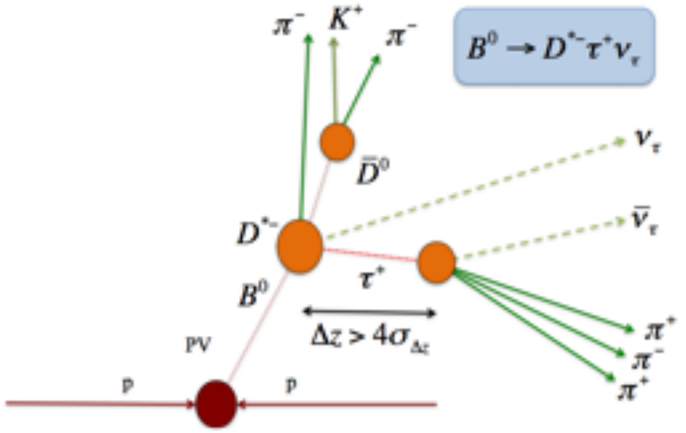

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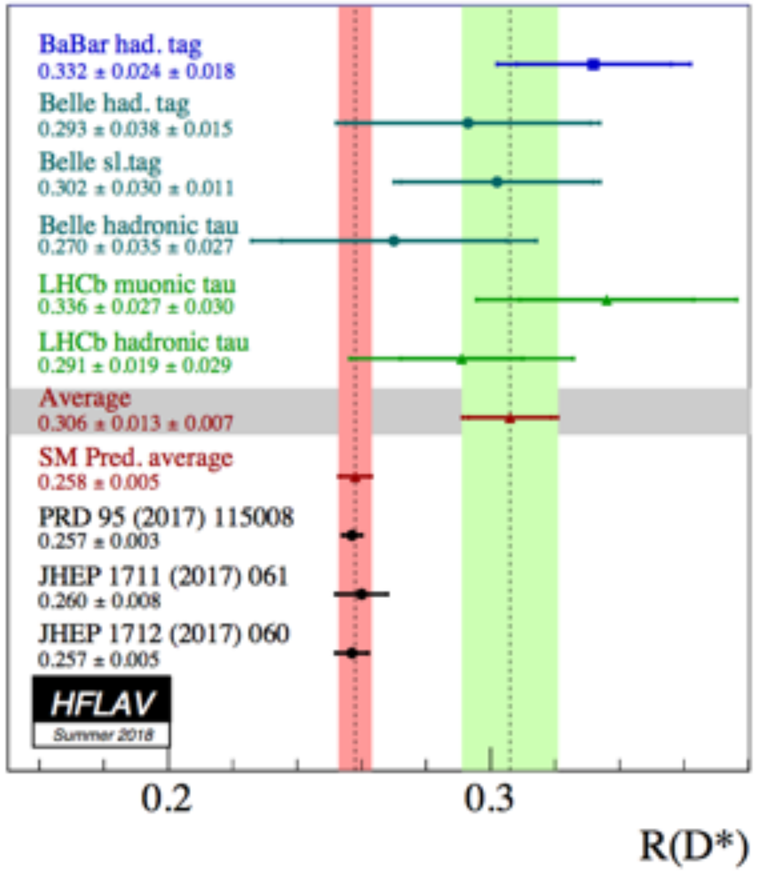
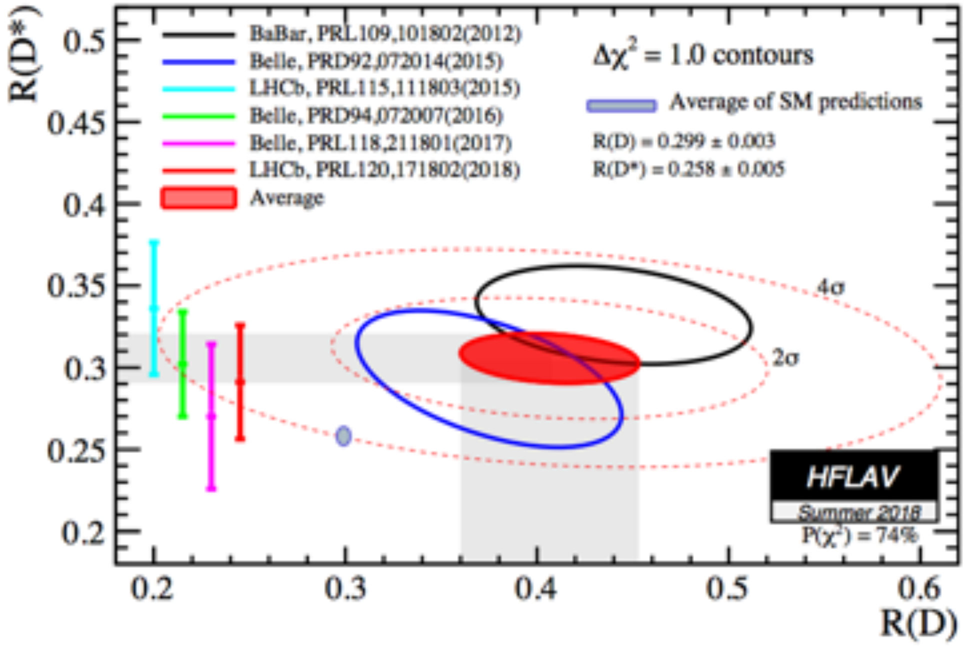
[∼4% precision, BaBar, Belle, LHCb]

[∼2% precision, HFLAV 2016]

comparing with Babar/Belle and to Standard Model





- All $R(D^*)$ measurements lie above the SM expectation (0.258 ± 0.005) [PRD95, 115008 (2017)], [JHEP 1711 (2017) 061], [JHEP 1712 (2017) 060]
- R_{D^*} world average: **3.0 σ** above SM prediction
- Combining $R(D) + R(D^*)$ measurements: **overall tension with SM of 3.8 σ**

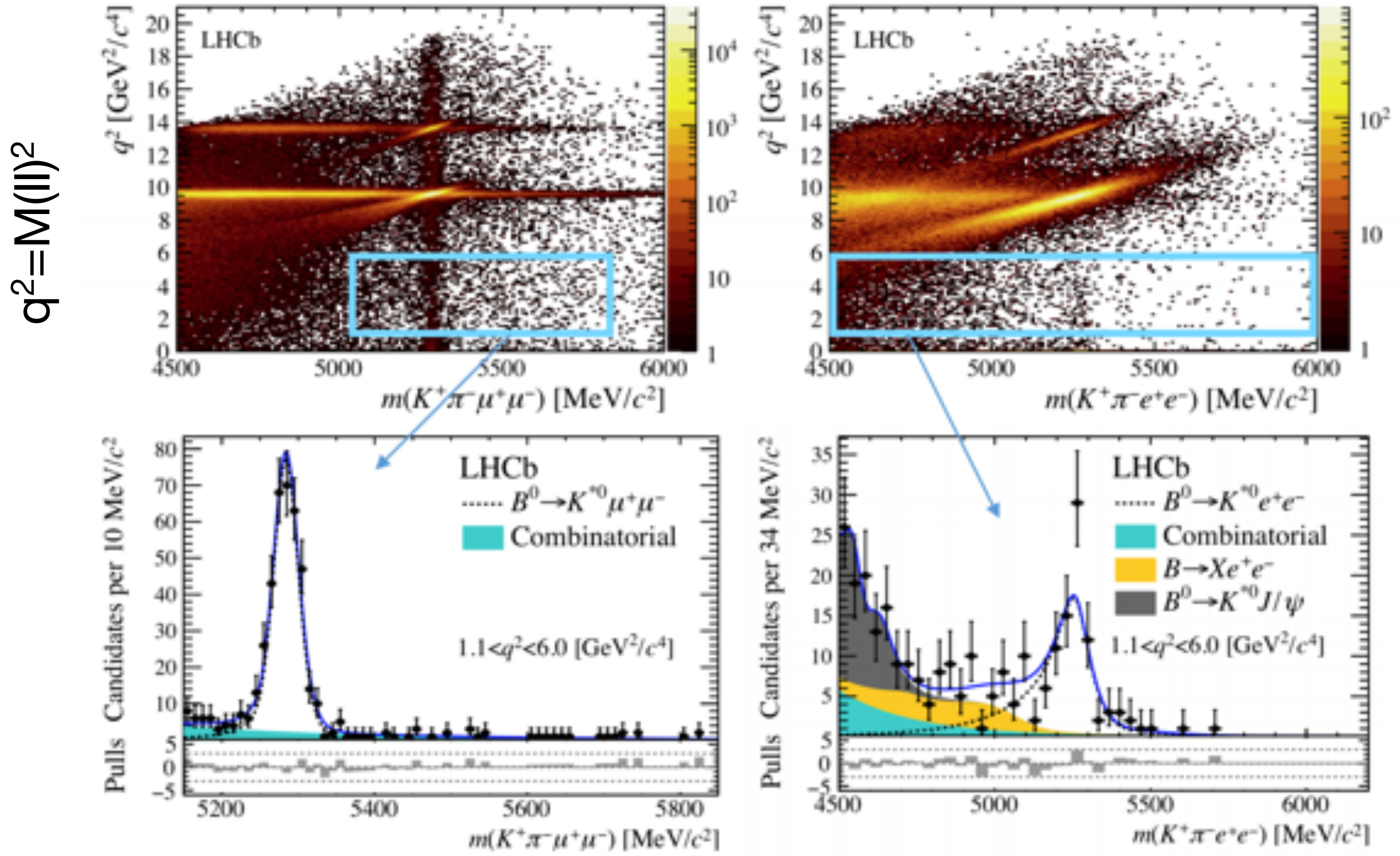
and this is Run-1 data. 2.5 more data from Run-2 still to analyse, and by 2020-2022 ten times more data

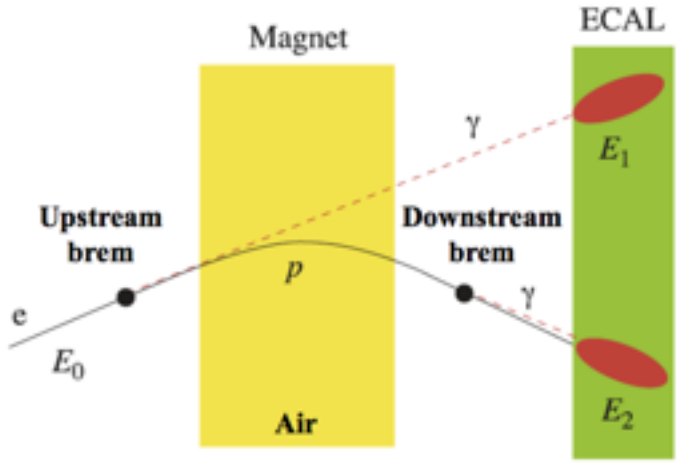
JHEP08 (2017) 055

R(K*)

Double ratio with respect to the resonant decay mode $B^0 \to K^{*0} J/\psi$

$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to(e^+e^-))}$$





electron worse due to Brehmsstrahlung

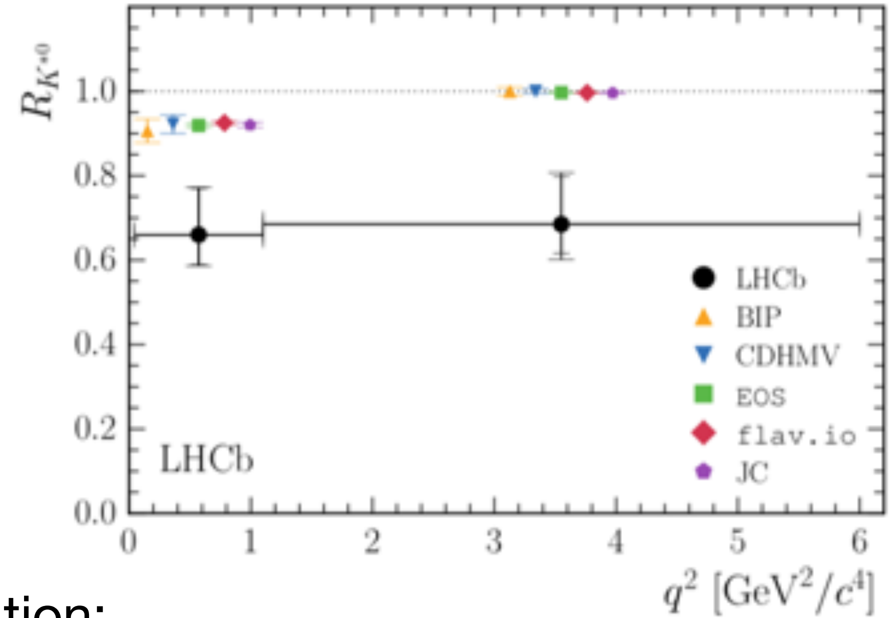
Event yield obtained from simultaneous M(K+pi−ℓ+ℓ−) fit to the J/ψ and non-resonant channels

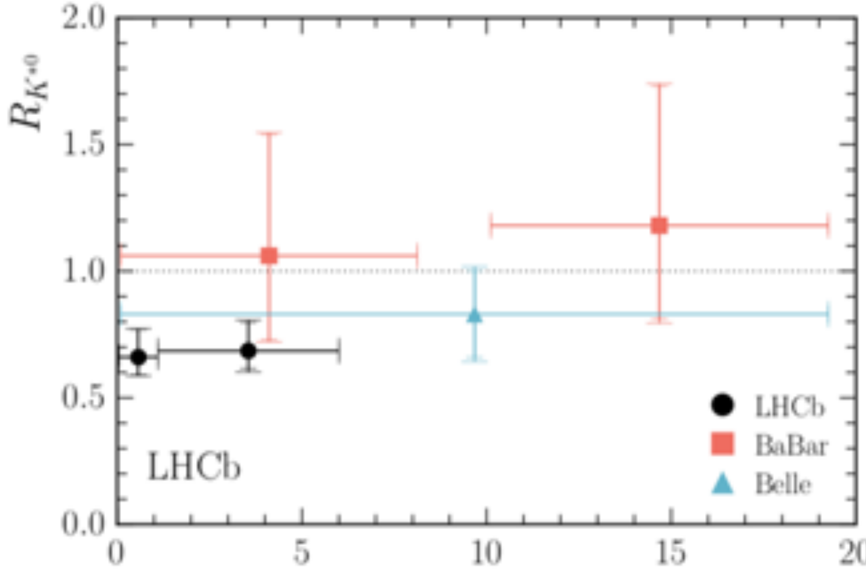
JHEP08 (2017) 055

Comparing with Babar/Belle and to Standard Model

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$

2.2 σ deviation from SM





[BaBar: PRD86(2012)032012]
[Belle: PRL103(2009)171801]

In addition:

ATLAS and CMS have also collected data during Run-2 to perform these measurements !

PRL 113, 151601 (2014)

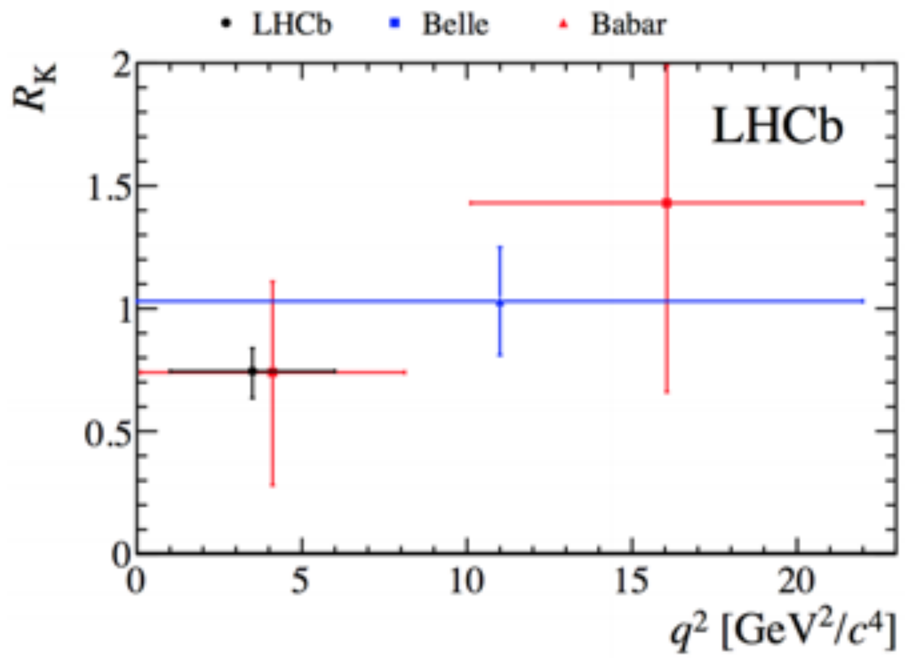
R(K)

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+ \mu\mu)}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B^+ \to K^+ ee)}{dq^2} dq^2} = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right)\left(\frac{N_{KJ/\psi(ee)}}{N_{KJ/\psi(\mu\mu)}}\right)\left(\frac{\epsilon_{Kee}}{\epsilon_{K\mu\mu}}\right)\left(\frac{\epsilon_{KJ/\psi(ee)}}{\epsilon_{KJ/\psi(\mu\mu)}}\right)$$

- As for R(K*) event yields determined using fits to the K+ℓ+ℓ- mass distribution

$$\mathbf{R(K)} = 0.745^{+0.090}_{-0.074}(\mathbf{stat.}) \pm 0.036(\mathbf{syst.})$$

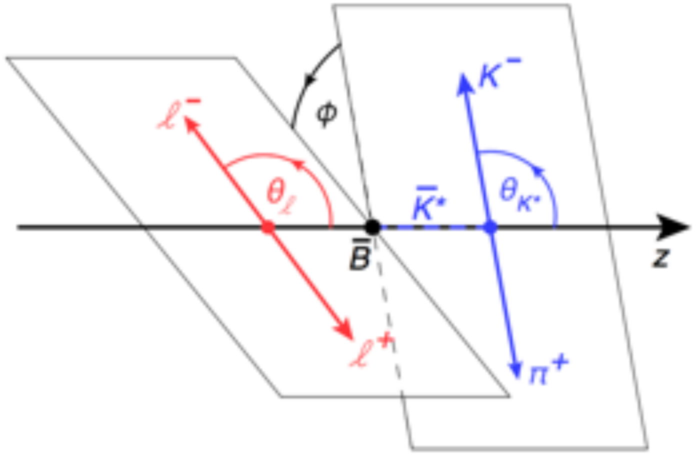
2.6σ from the SM *



* SM prediction for $R_K = 1 \pm 0.01$

Bordone, Isidori Eur.Phys.J. C76 (2016) no.8, 440

R(K*)

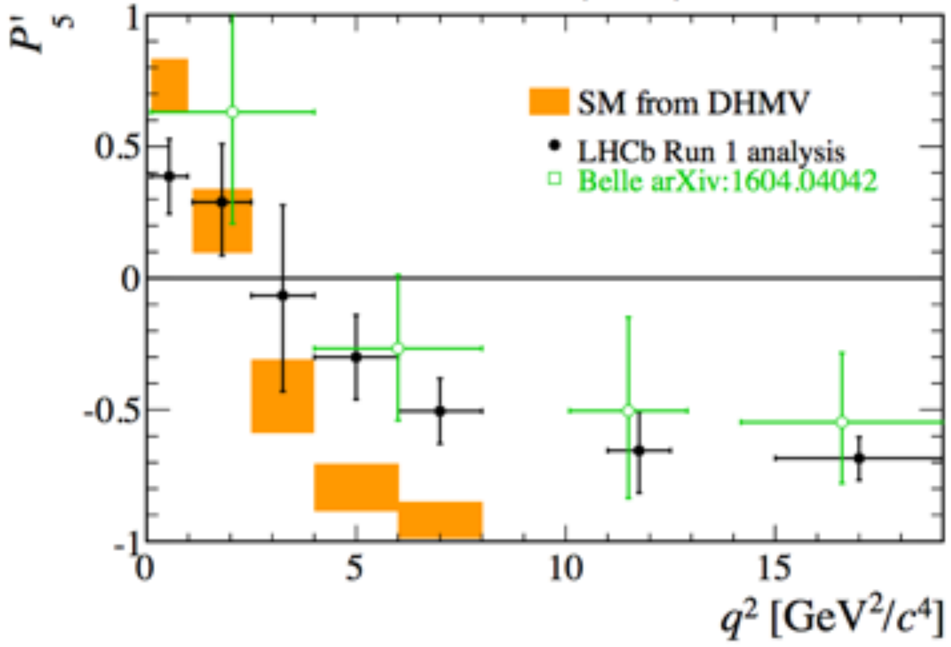


NP models which explain the observed discrepancies in the measurement of R(K(*)) w.r.t SM predictions, foresee anomalous behaviours also in the angular distribution of the decay B0→ K*0 ll.

One of the angular observables in which the differential decay width can be parametrised is P5’ (reduced dependence on hadronic form-factors)

- Global fit at **3.4 σ** from the SM prediction
- Explainable in terms of:
  - SM charm-loop effects (cannot explain tension in R(K(*))) *
  - New Physics

JHEP 02 (2016) 104



* JHEP 06 (2016) 116 (non-factorizable corrections in the region of $q^2 << 4m^2_c$)

Possible explanation for B decays anomalies?

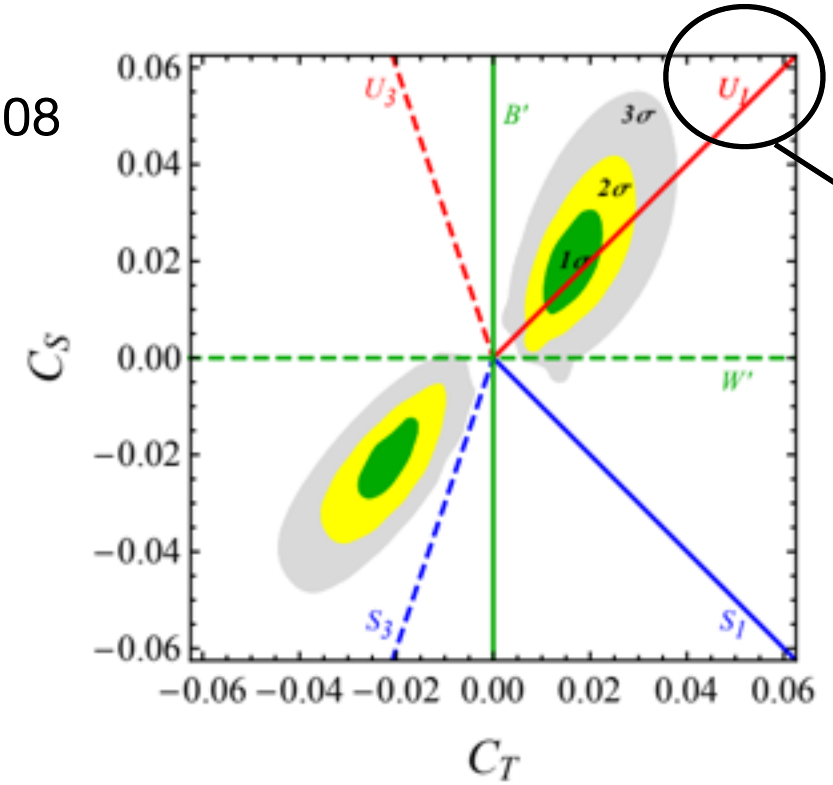
Javier Fuentes Martin, Theoretical status of Flavour anomalies, Discrete 2018

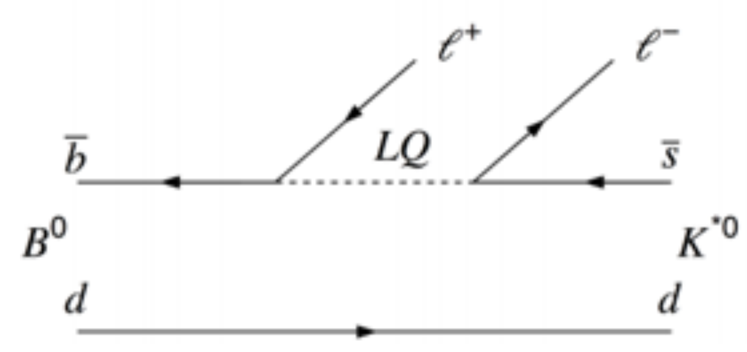
what do we know?
- more enhanced with 3rd family than with 2nd family
- would indicate NP ~ 1 TeV scale
- not unusual to see preference wrt flavour eg.Higgs

great example of how first pass at EFT gives idea for which type of models could explain the results.

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

arXiv: 1706.07808





vector lepto-quarks

testable
at LHC now

to fit additional observables from LHC
—> new gauge group SU(4) —> in addition to U1, also a g' (coloron) and Z' , range 2-4 TeV