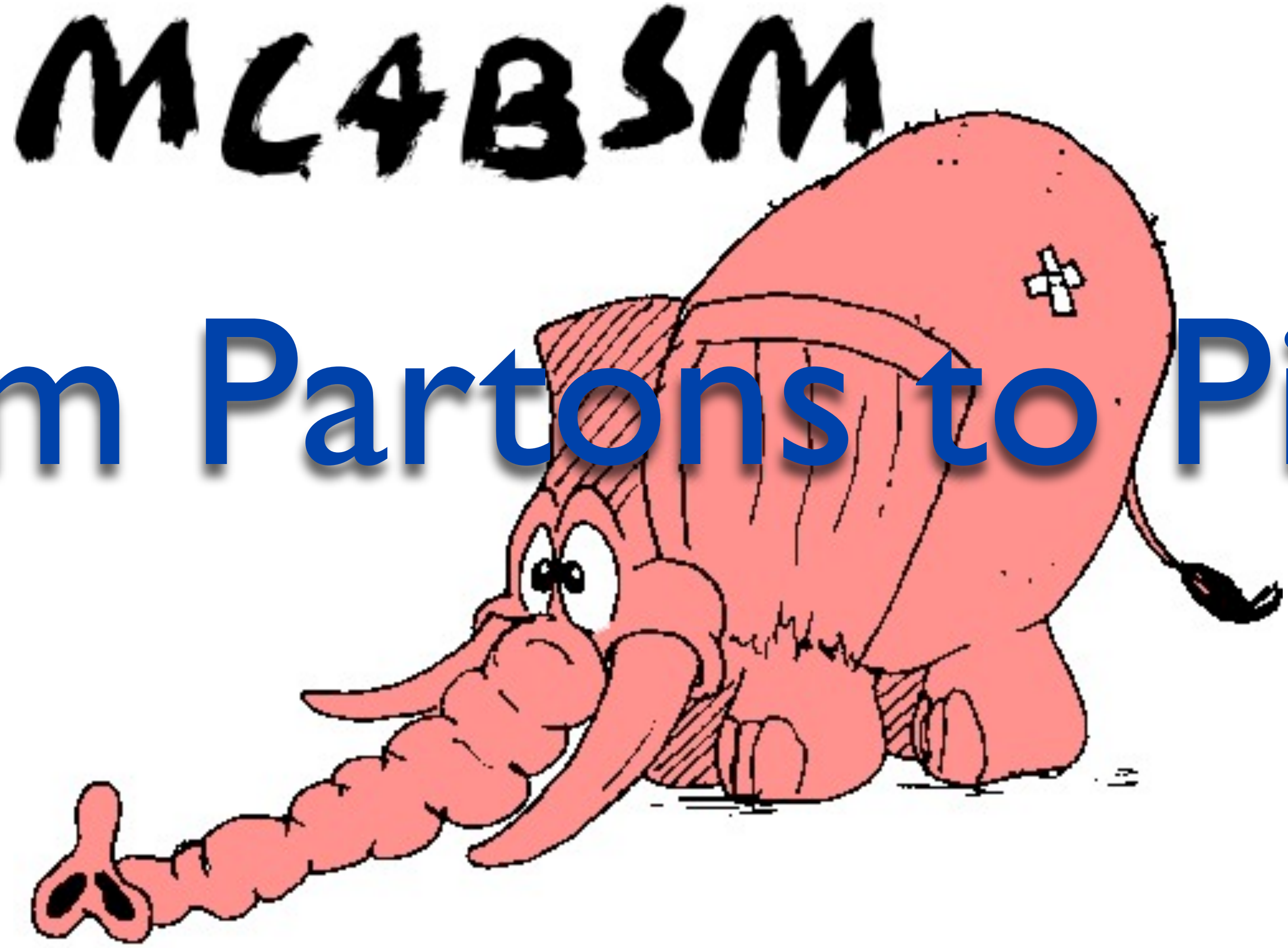


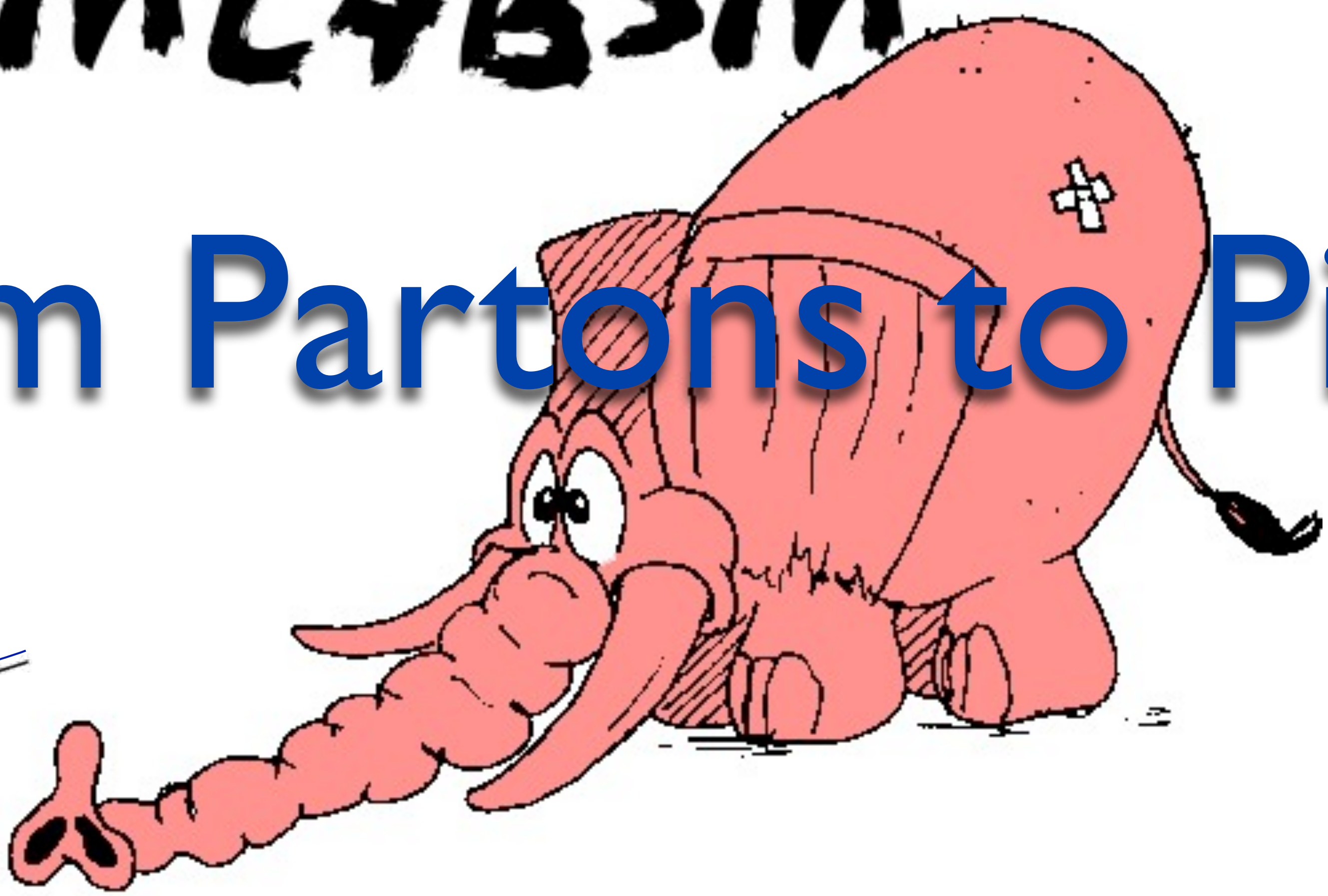
From Partons to Pions

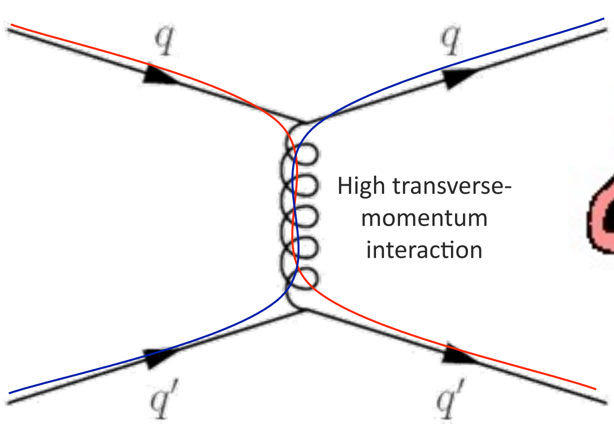
Peter Skands (CERN-TH)

5th MC for BSM Workshop
Copenhagen, April 2010

MC4BSM

From Partons to Pions





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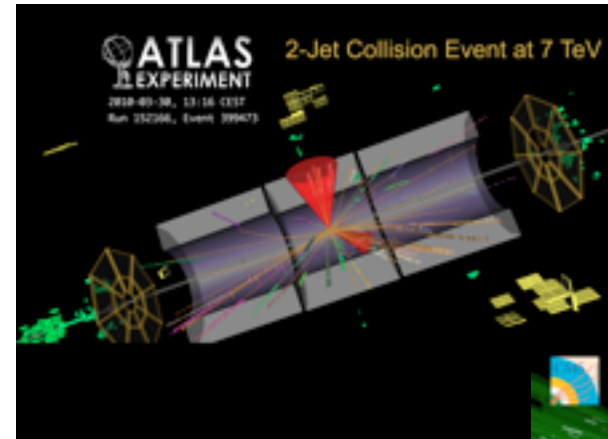

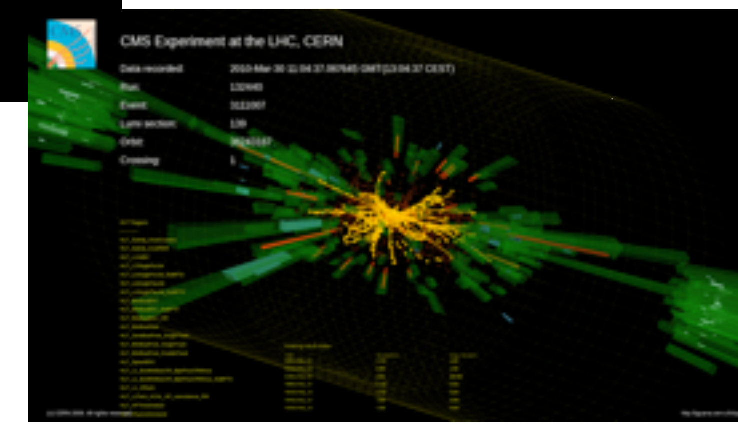

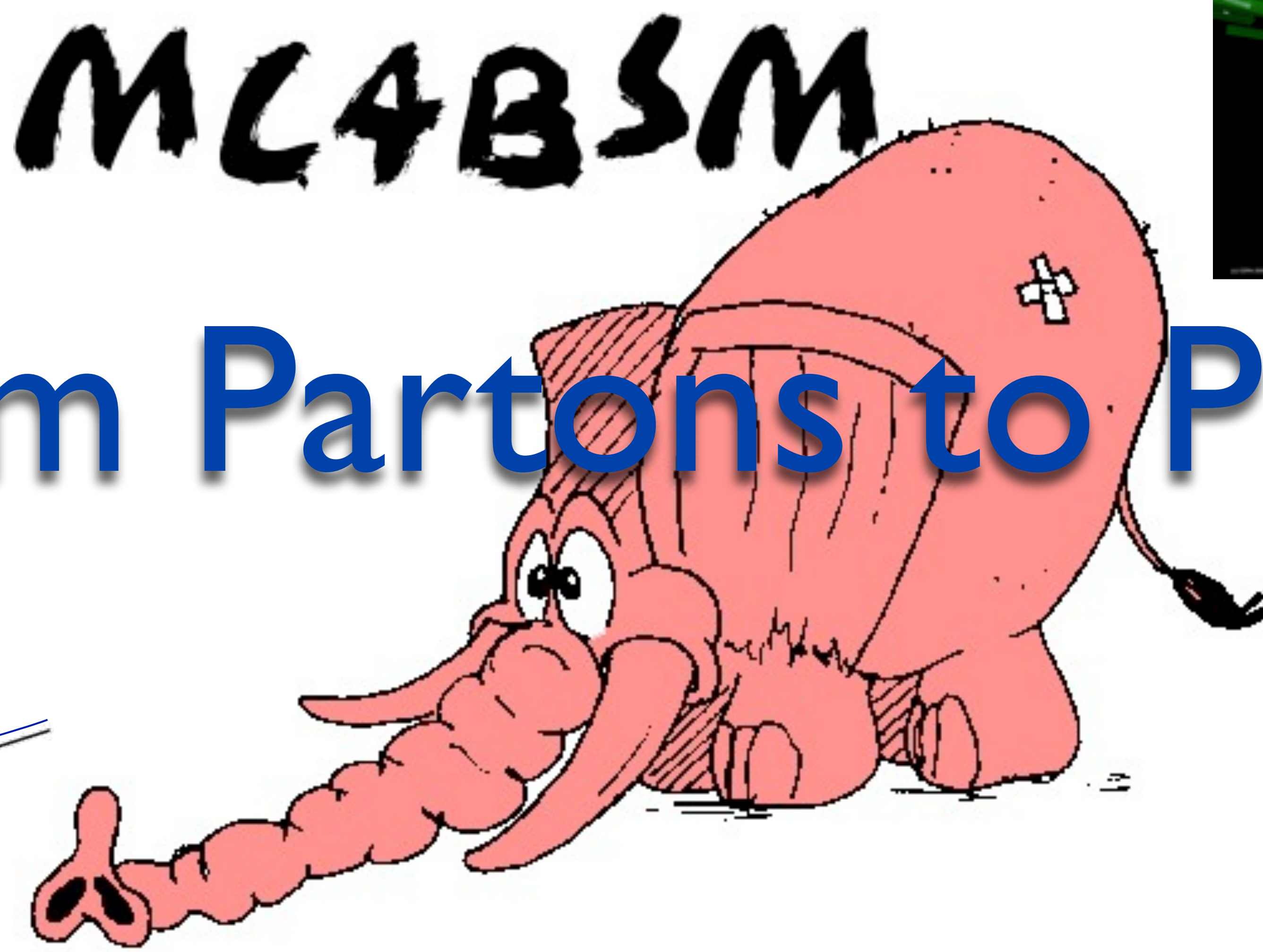

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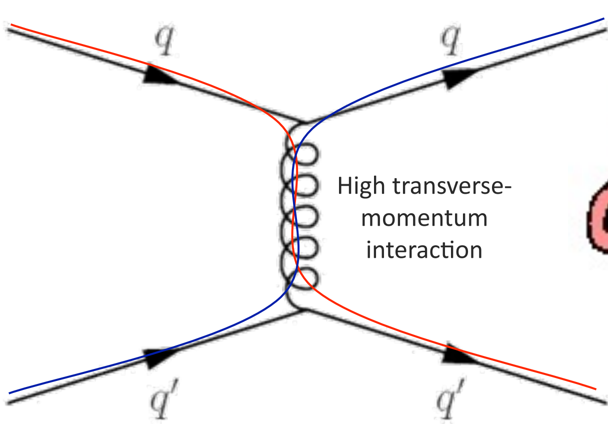

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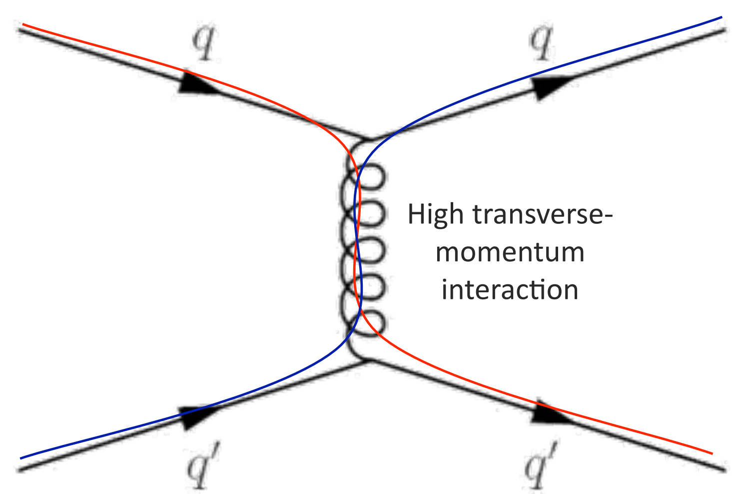
Calculating Collider Observables



- Main Tool: Lowest-Order Matrix Elements calculated in a fixed-order perturbative expansion

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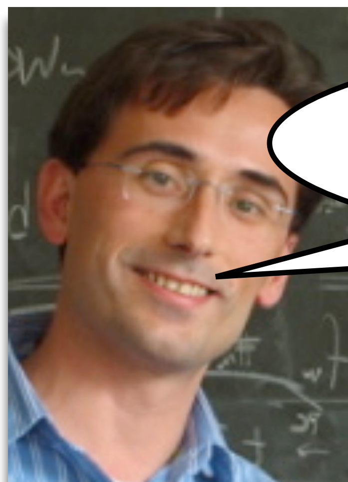
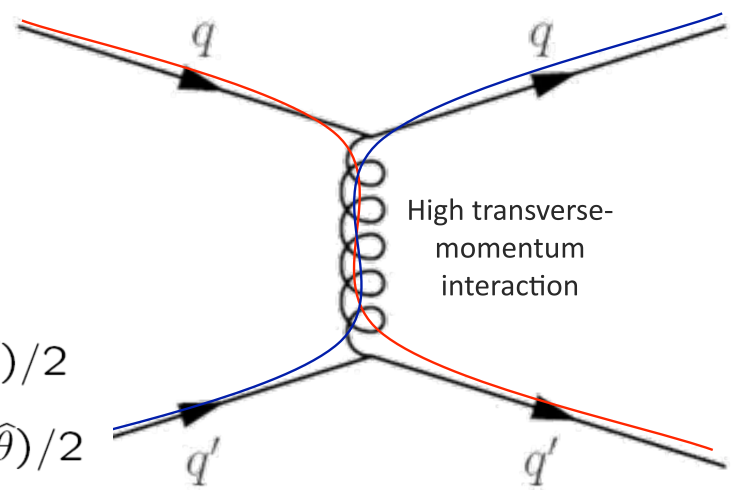


$$qq' \to qq' \quad : \quad \frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi}{\hat{s}^2}\frac{4}{9}\alpha_s^2\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$$

$$\hat{s} = (p_1 + p_2)^2$$
$$\hat{t} = (p_1 - p_3)^2 = -\hat{s}(1 - \cos\hat{\theta})/2$$
$$\hat{u} = (p_1 - p_4)^2 = -\hat{s}(1 + \cos\hat{\theta})/2$$



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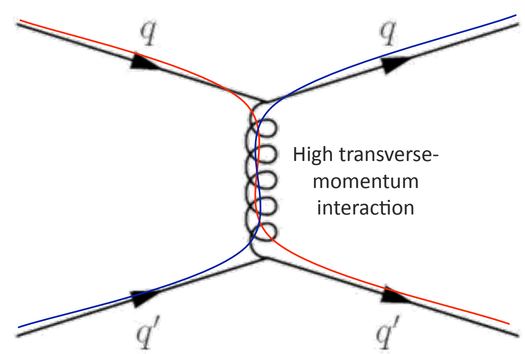

From Partons to Pions

Disclaimer

*"**It is a** huge mistake to theorize before one has data - One tends to twist fact to suit theory, instead of theory to suit fact"*

Sherlock Holmes (2009)

Complications

Born = ***Leading Order*** and ***Totally Inclusive***

Radiative corrections

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Hadronization, Underlying Event,
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- **Observables** should be **physical and IR safe**

Additional Sources of Particle Production

- ► Starting point: Matrix Elements
  - 2→n hard parton scattering at (N)LO

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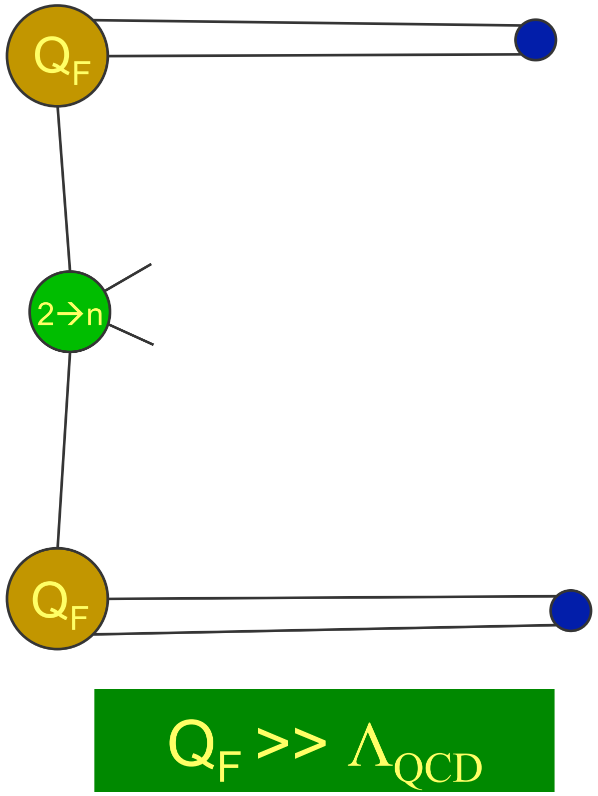

Monte Carlo at Fixed Order

High-dimensional problem (phase space)

d≥5 ➔ Monte Carlo integration

"Monte Carlo": N. Metropolis, first Monte Carlo calculation on ENIAC (1948), basic idea goes back to Enrico Fermi

"Experimental" distribution of observable $\mathcal{O}$ in production of X:

Fixed Order (all orders)

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right|_{\mathrm{ME}} = \sum_{k=0} \int \mathrm{d}\Phi_{X+k} \left| \sum_{\ell=0} M^{(\ell)}_{X+k} \right|^2 \delta(\mathcal{O} - \mathcal{O}(\{p\}_{X+k}))$$

k : legs

ℓ : loops

{p} : momenta

Note 1: For k larger than a few, need to be quite clever in phase space sampling

Note 2: For $k+\ell > 0$, need to be careful in arranging for real-virtual cancellations

Principal virtues

1. Stochastic error $O(\mathcal{N}^{-1/2})$ independent of dimension
2. Full (perturbative) quantum treatment at each order
3. (KLN theorem: finite answer at each (complete) order)

A Log on Fire

- Naively, brems suppressed by $\alpha_s \sim 0.1$
  - Truncate at fixed order = LO, NLO, …
  - However, if ME >> 1 → can't truncate!

Z > q(x_1) qbar(x_2) g($2-x_1-x_2$)

$$\boxed{\frac{1}{\sigma}\frac{d^2\sigma}{dx_1 dx_2} = \frac{2\alpha_s}{3\pi}\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)}}$$

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- ▶ Example: SUSY pair production at 14 TeV, with MSUSY ~ 600 GeV

LHC - sps1a - m~600 GeV   Plehn, Rainwater, PS PLB645(2007)217

FIXED ORDER pQCD	$\sigma_{\rm tot}$[pb]	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} >$ 100 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive **X + 1 "jet"** →	σ_{1j}	2.89	2.74	0.136	0.145	0.73
inclusive **X + 2 "jets"** →	σ_{2j}	1.09	0.85	0.049	0.039	0.26
$p_{T,j} >$ 50 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	5.90	5.37	0.283	0.285	1.50
	σ_{2j}	4.17	3.18	0.179	0.117	1.21

(Computed with SUSY-MadGraph)

Cross section for 1 or more 50-GeV jets larger than total σ, obviously non-sensical

- Conclusion: 100 GeV can be "soft" at the LHC
  - Matrix Element (fixed order) expansion breaks completely down at 50 GeV
  - With decay jets of order 50 GeV, this is important to understand and control

Alwall, de Visscher, Maltoni, JHEP 0902(2009)017

The Way of the Chicken

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  - Sum inclusively over all QCD
    - Leptons almost IR safe by definition
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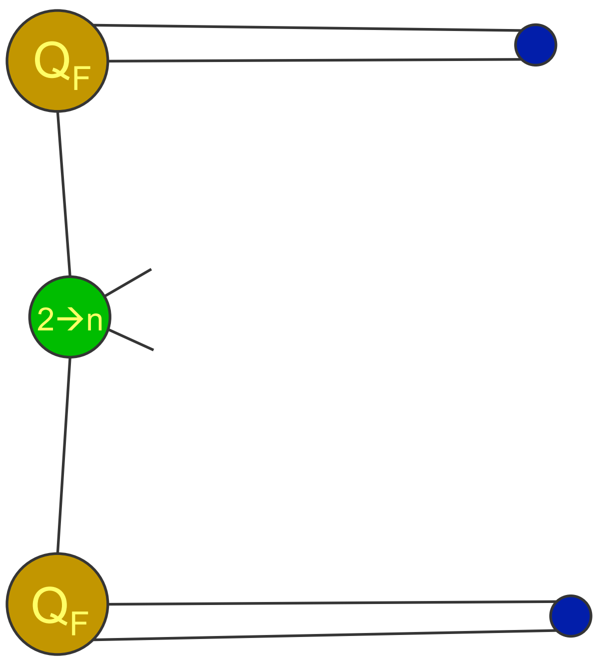

$Q_F >> \Lambda_{QCD}$

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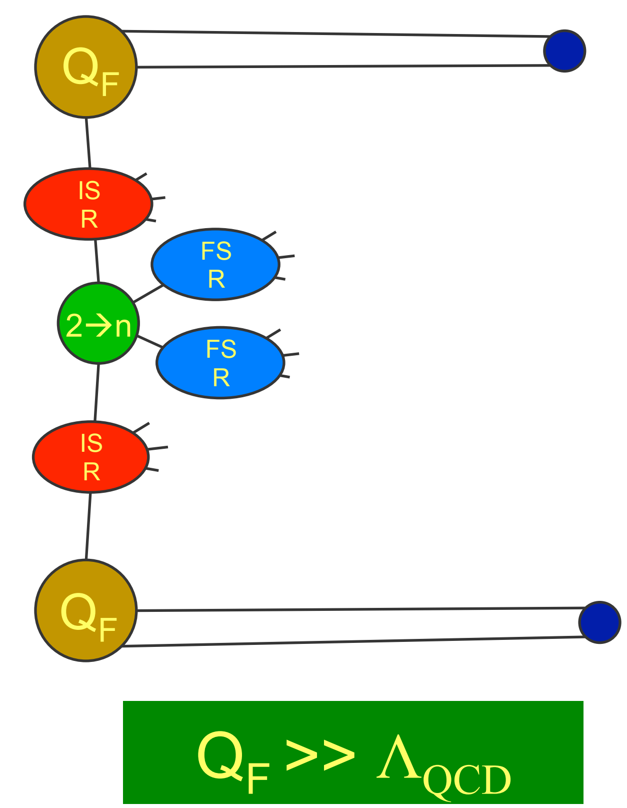

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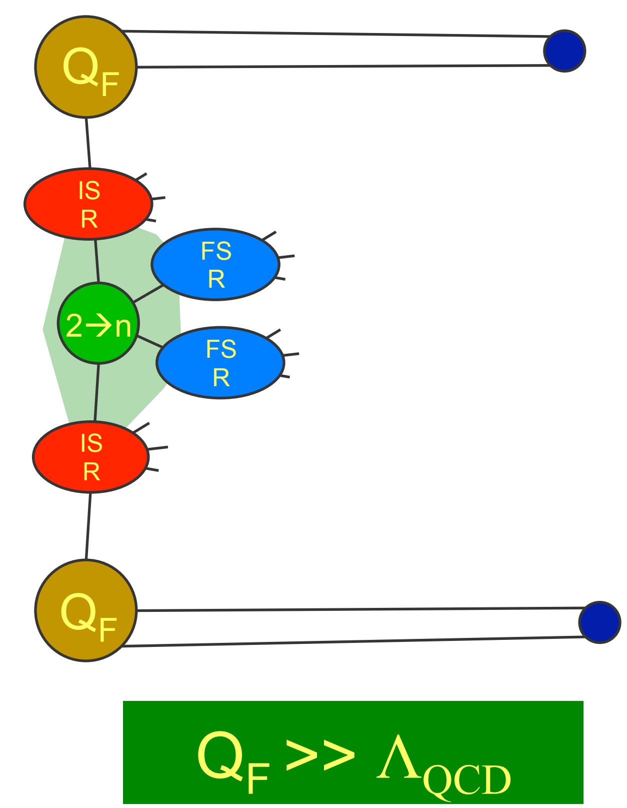
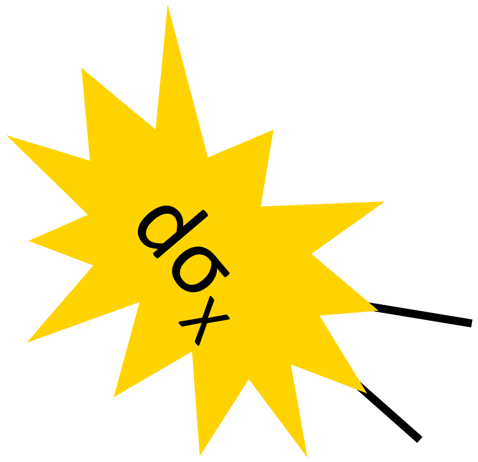
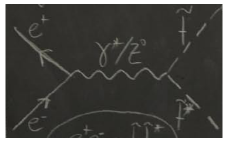


Bremsstrahlung



$$\mathrm{d}\sigma_X = \ldots$$ 

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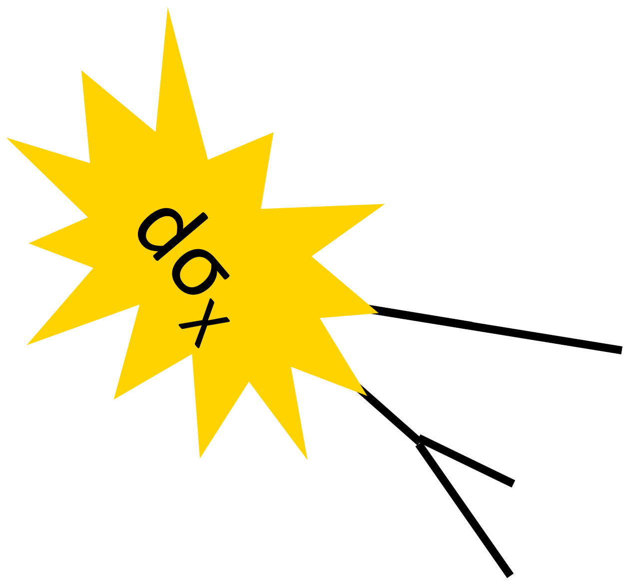
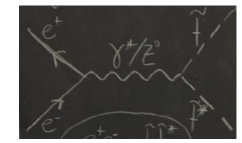


$$\mathrm{d}\sigma_X = \ldots$$ 

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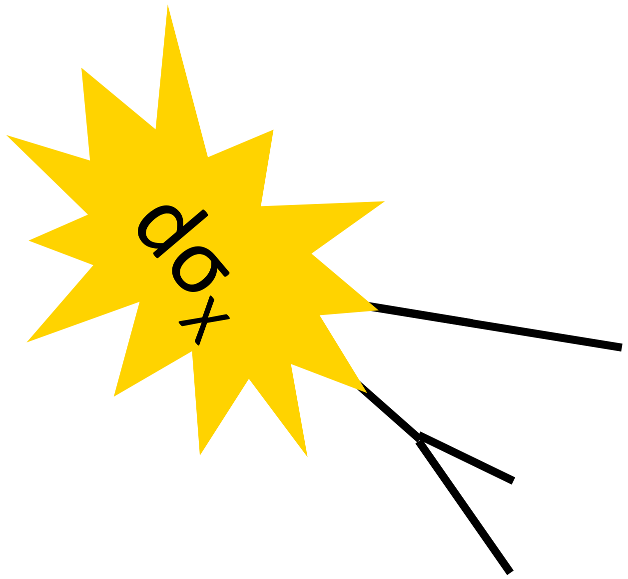
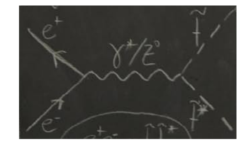


$$\mathrm{d}\sigma_X = \ldots$$ 

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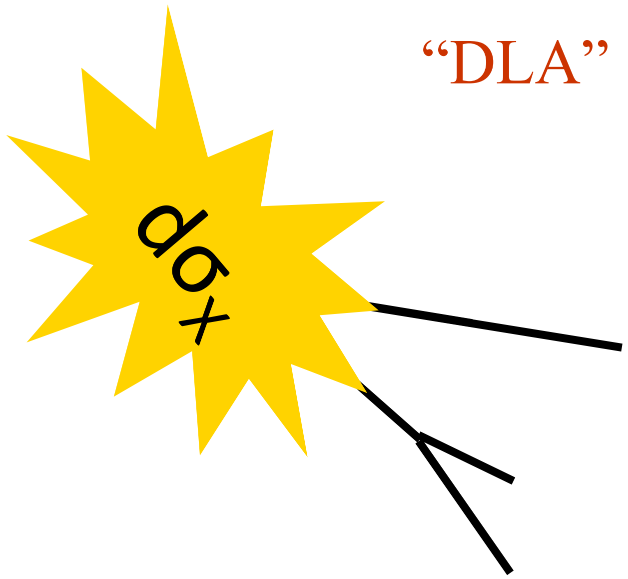
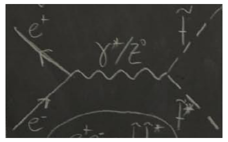


"DLA" $\dfrac{\alpha\, s_{ab}}{s_{ai} s_{ib}}$

$$d\sigma_X = \ldots$$ 

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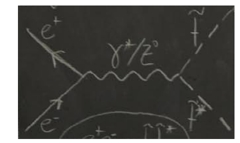

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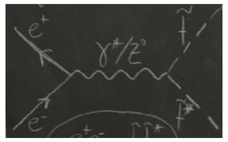
$$\mathrm{d}\sigma_X = \ldots$$ 

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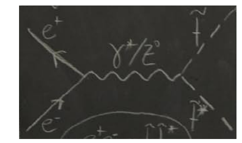
$$d\sigma_X = \ldots$$ 

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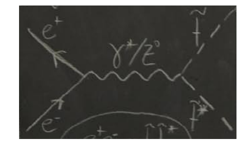
$d\sigma_X = \ldots$ 

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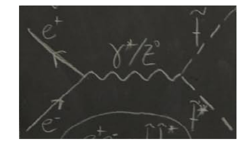
$$d\sigma_X = \ldots$$ 

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Interpretation: the structure evolves

But something’s not right…

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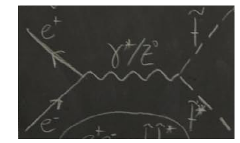
$$d\sigma_X = \ldots$$ 

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This is an approximation to inifinite-order tree-level cross sections

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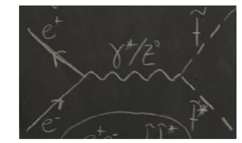
$$d\sigma_X = \ldots$$ 

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KLN

+ UNITARITY:

Virt = – Int(Tree) + F

(or: given a jet definition, an event has *either* 0, 1, 2, or *n* jets)

$$\begin{aligned} \sigma_{X;\mathrm{excl}} &= \sigma_X - \sigma_{X+1} \\ &= \sigma_X - \sigma_{X+1;\mathrm{excl}} - \sigma_{X+2;\mathrm{excl}} - \ldots \end{aligned}$$

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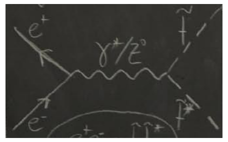
$$d\sigma_X = \ldots$$ 

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$$\sigma_{X+1}(Q) = \sigma_{X;\mathrm{incl}} - \sigma_{X;\mathrm{excl}}(Q)$$

This includes both real and virtual corrections

$$\begin{aligned} \sigma_{X;\mathrm{excl}} &= \sigma_X - \sigma_{X+1} \\ &= \sigma_X - \sigma_{X+1;\mathrm{excl}} - \sigma_{X+2;\mathrm{excl}} - \ldots \end{aligned}$$

Matching

- A (Complete Idiot's) Solution – Combine
  1. $[X]_{ME}$ + showering
  2. $[X + 1 \text{ jet}]_{ME}$ + showering
  3. …

Run generator for X (+ shower)

Run generator for X+1 (+ shower)

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Combine everything into one sample

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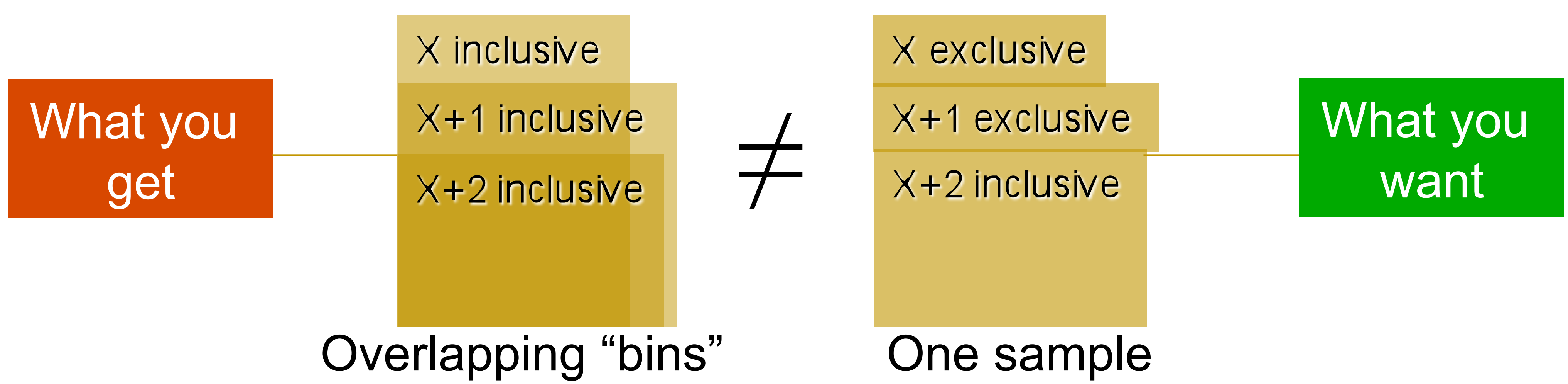
- Doesn’t work
  - [X] + shower is inclusive
  - [X+1] + shower is also inclusive



The Matching Game

- Shower off X already contains LL part of all X+n

$$\mathrm{d}\sigma_{X+1} \sim 2g^2 \mathrm{d}\sigma_X \frac{\mathrm{d}s_{a1}}{s_{a1}} \frac{\mathrm{d}s_{1b}}{s_{1b}}$$

- Adding back full ME for X+n would be overkill

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Seymour, CPC90(1995)95
+ many more recent …

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$w_X \quad = |M_X|^2 \qquad + \text{Shower}$

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HERWIG: for X+1 @ LO (Shower = 0 in dead zone of angular-ordered shower)

MC@NLO: for X+1 @ LO and X @ NLO (note: correction can be negative)

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One event sample

$w_X = |M_X|^2$ + *Shower*

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$R_{X+1} = |M_{X+1}|^2/\mathit{Shower}\{w_X\}$ + *Shower*

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VINCIA: for all X+n @ LO and X @ NLO (only worked out for decay processes so far)

Remaining Uncertainties

- In a (matched) shower calculation, there are many dependencies on things not traditionally found in matrix-element calculations:
- The final answer will depend on:
  - The choice of shower evolution “time”
  - The splitting functions (finite terms not fixed)
  - The phase space map (“recoils”, $d\Phi_{n+1}/d\Phi_n$)
  - The renormalization scheme (vertex-by-vertex argument of α_s)
  - The infrared cutoff contour (hadronization cutoff)
  - + Matching prescription and “matching scales”

Variations →

Comprehensive uncertainty estimates

(showers with uncertainty bands)

Matching to MEs (& N^{n}LL?) →

Reduced Dependence

(systematic reduction of uncertainty)

The way of the Fox

► I'll use semi-inclusive observables

- Sum inclusively over the worst parts of QCD
  - IR safety → N.P. corrs suppressed by Q_{had}
  - → IR safe **jet algs (e.g., FASTJET)**
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  - High precision = **more higher orders** → **more QCD**
- Large hierarchies (s, m_1, m_2, p_{Tjet1}, p_{Tjet2}, …) → Careful !
  - **Huge jet rate enhancements :** perturbative series "blows up"
  - → cannot truncate at any fixed order
    - For 600 GeV particles, **a 100 GeV jet can be "soft"**
  - Use infinite-order **approximations** = parton showers
    - Only "LL" → not highly precise + only good when **everything** is hierarchical
    - Need to combine with explicit matrix elements → **matching**
    - Still, non-factorizable + non-pert corrections set an **ultimate** limit

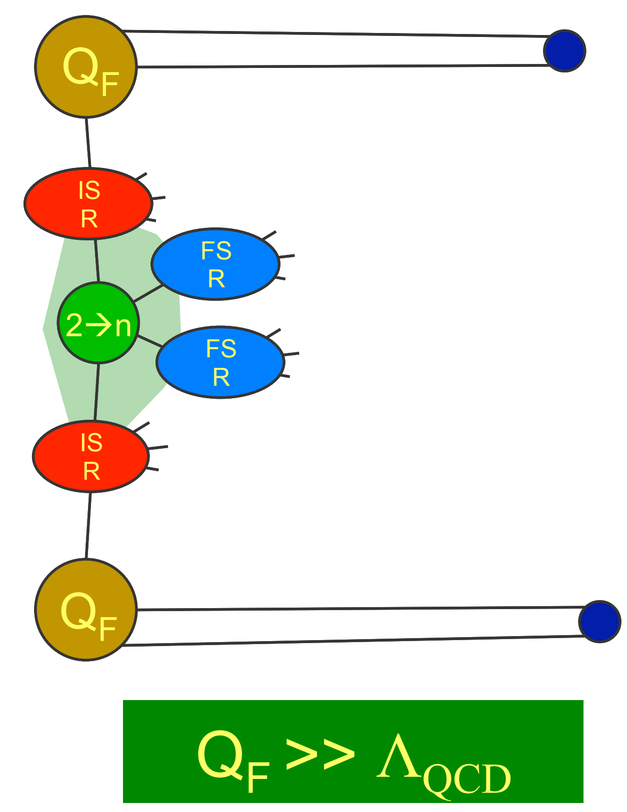
Additional Sources of Particle Production

- Starting point: Matrix Elements + Parton Showers

n = a handful
+ resonance
decays

2→n hard parton scattering at (N)LO

+ Bremsstrahlung ➔ 2→∞ at (N)LL



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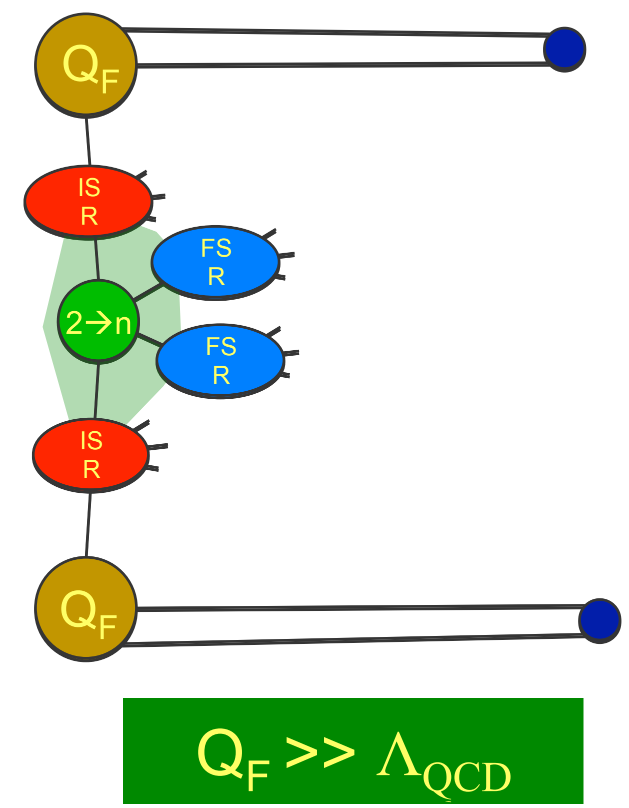

Hadrons are not elementary
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e.g. 4→4, 3→ 3, 3→2

Underlying Event has perturbative part!

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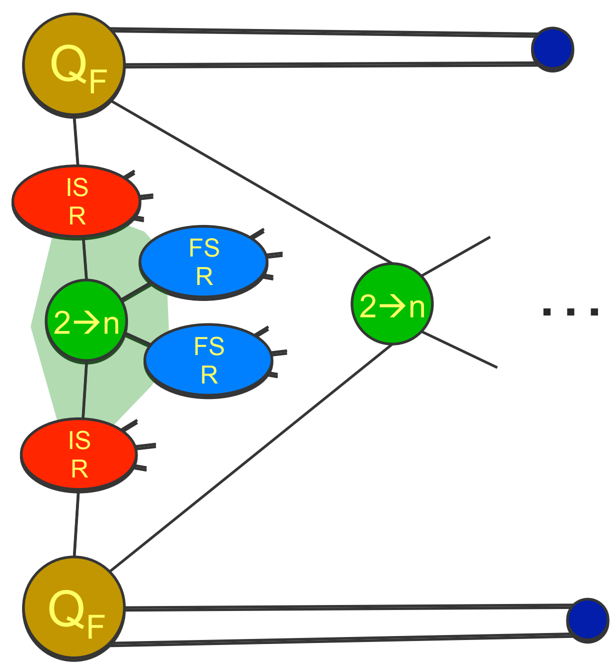

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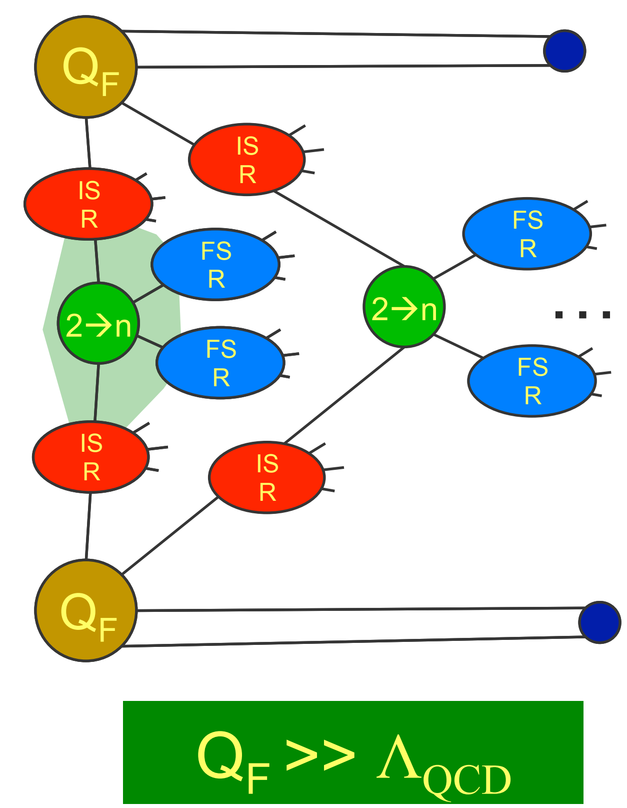

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▶ No factorization theorem

➔Herwig++, Pythia, Sherpa: MPI models

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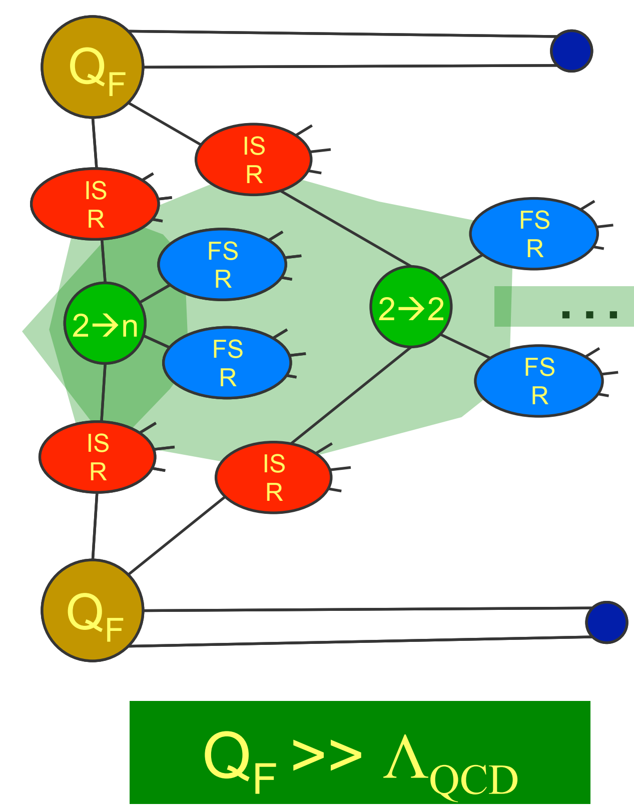

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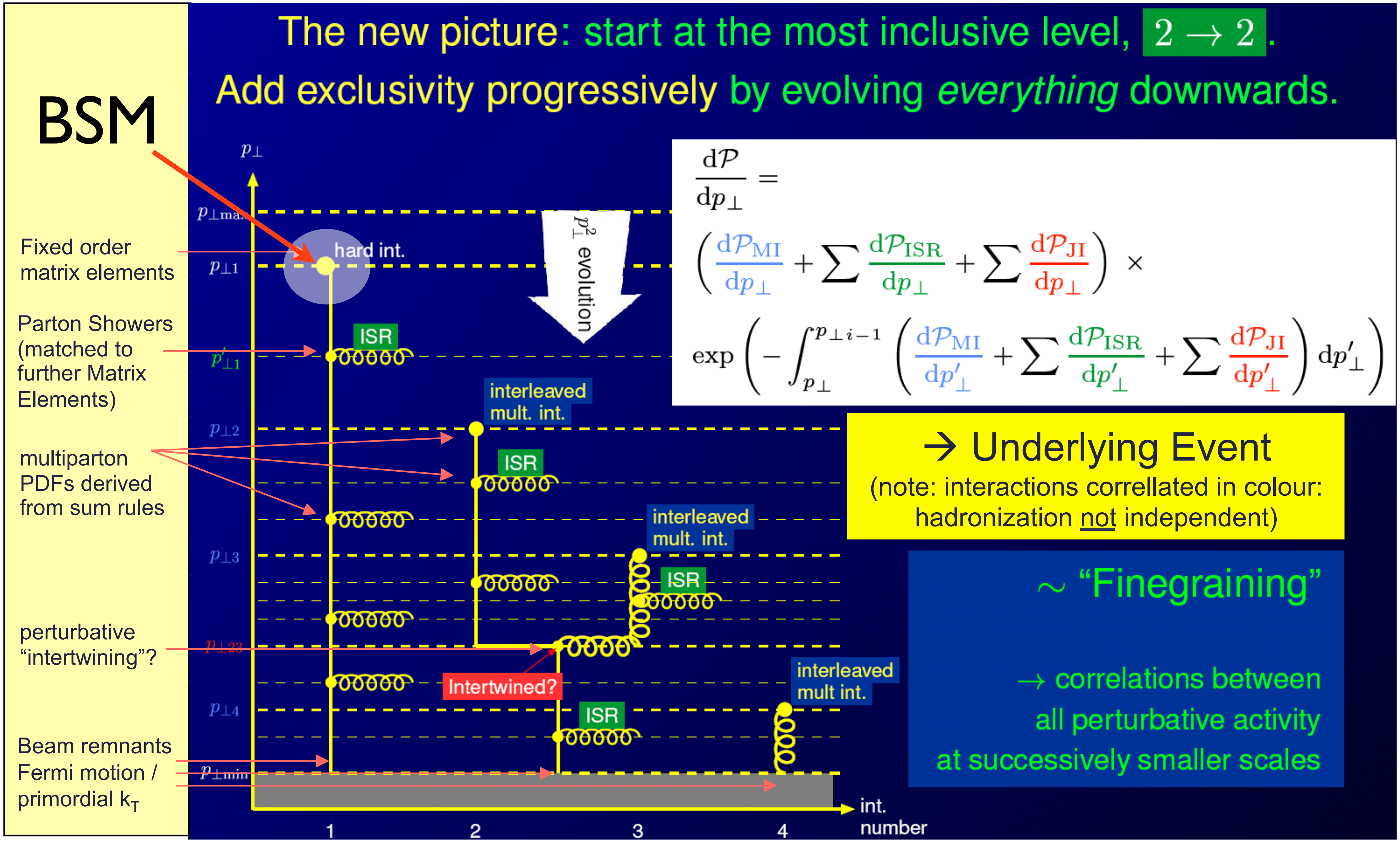
Underlying Event: The Interleaved Idea



Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129

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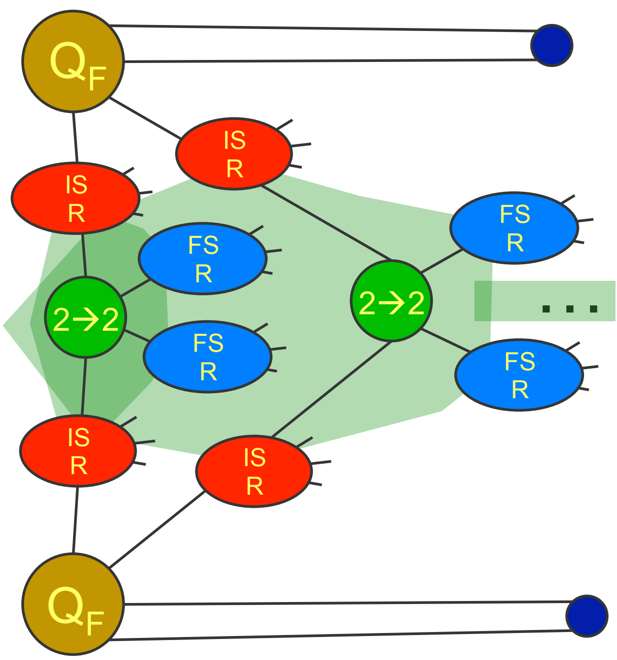
ME+ISR/FSR

+ perturbative MPI

+

Stuff at

$Q_F \sim \Lambda_{QCD}$



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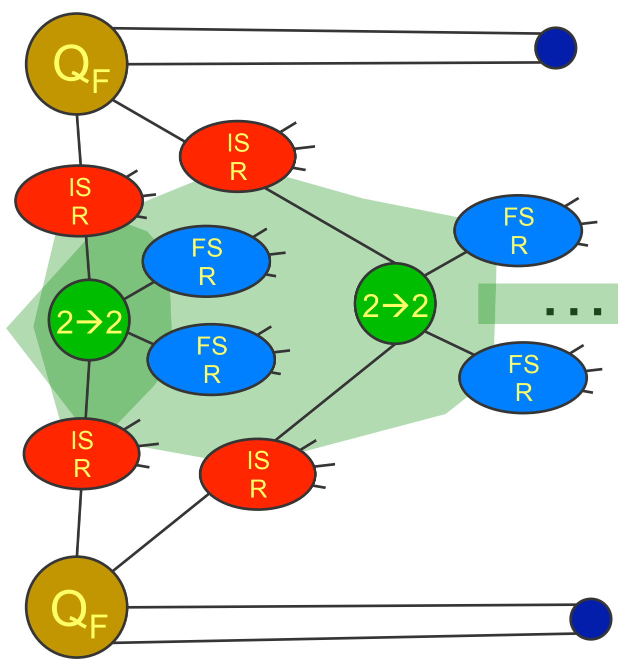
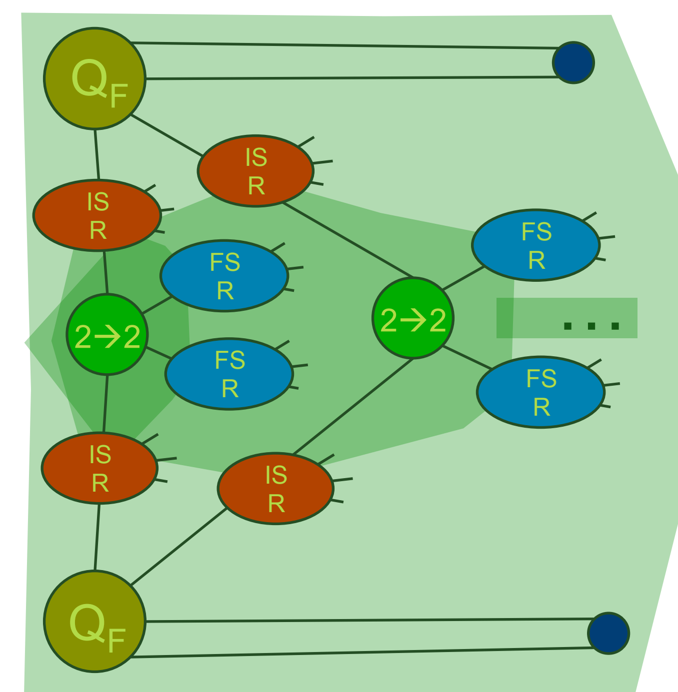
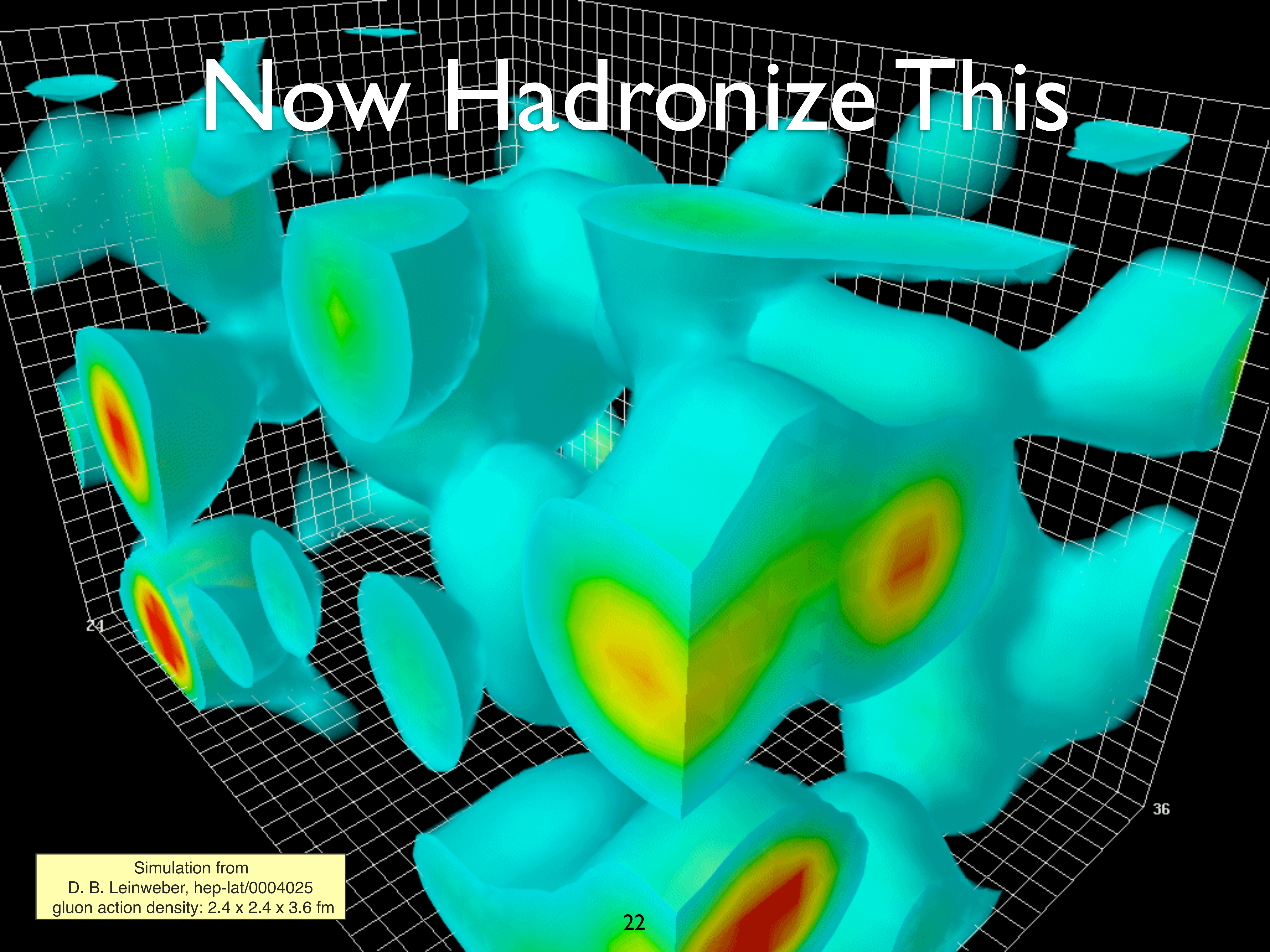




Need-to-know issues for IR sensitive quantities (e.g., N_{ch})

Now Hadronize This



Simulation from
D. B. Leinweber, hep-lat/0004025
gluon action density: 2.4 x 2.4 x 3.6 fm

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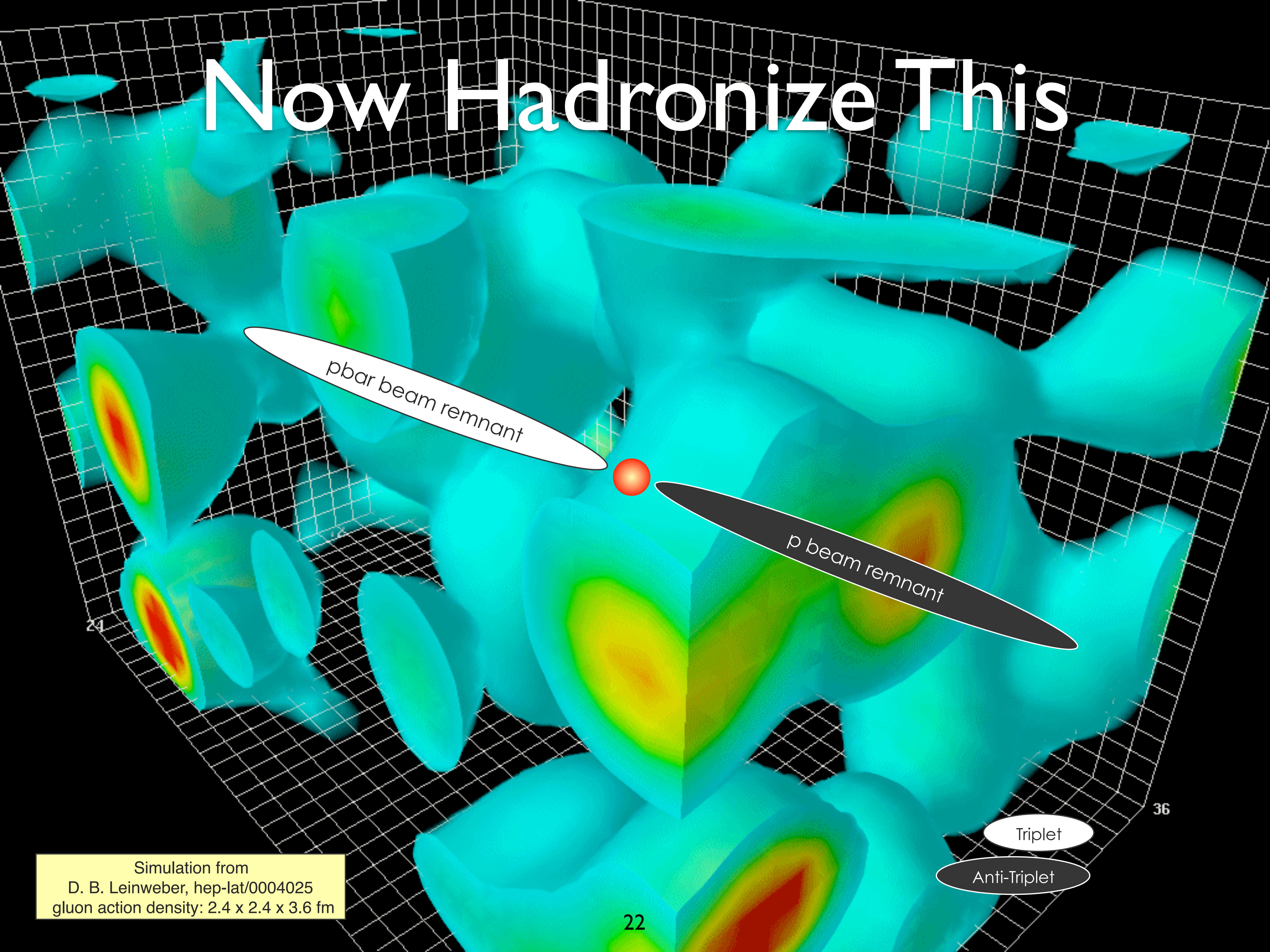

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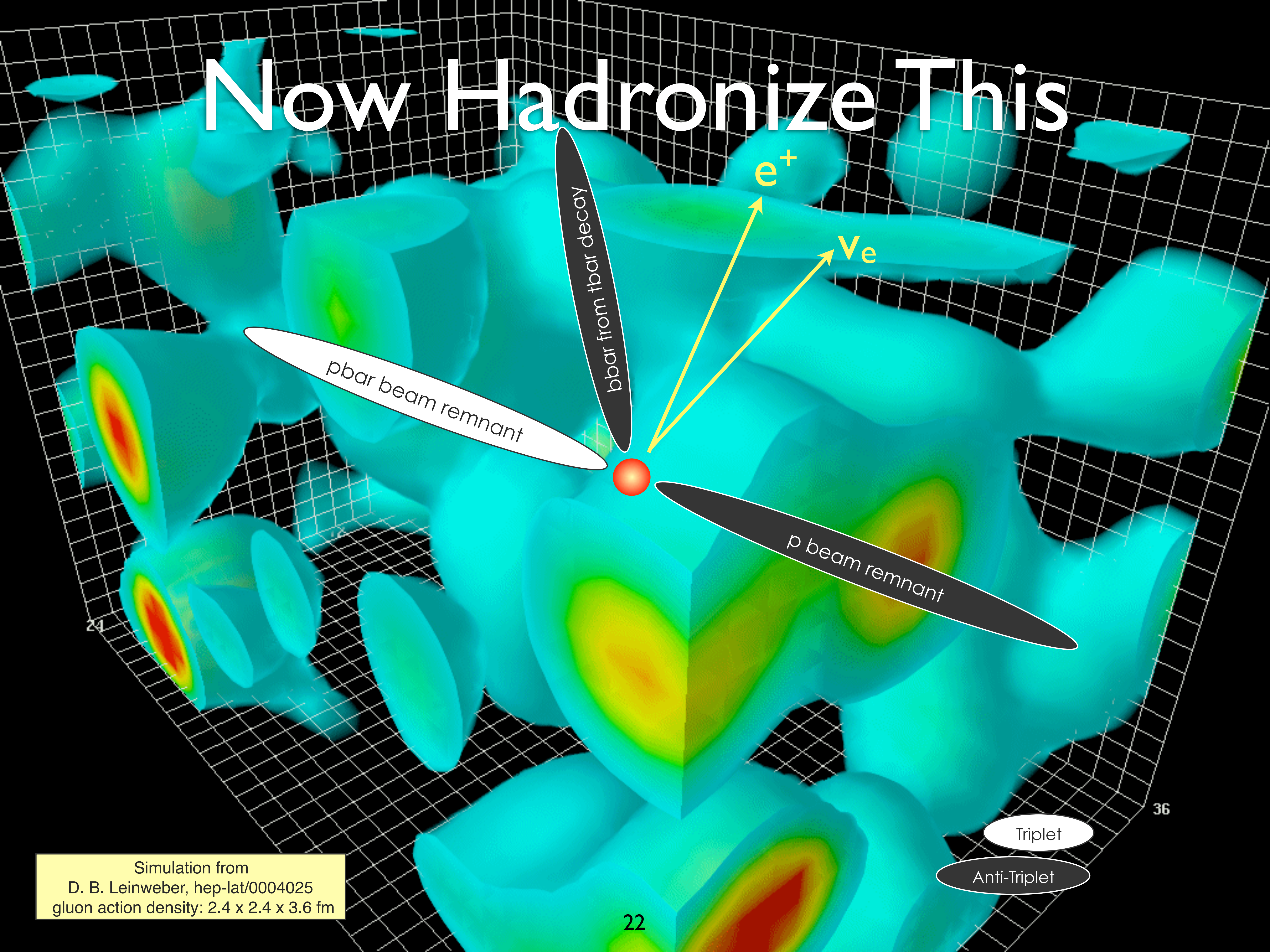

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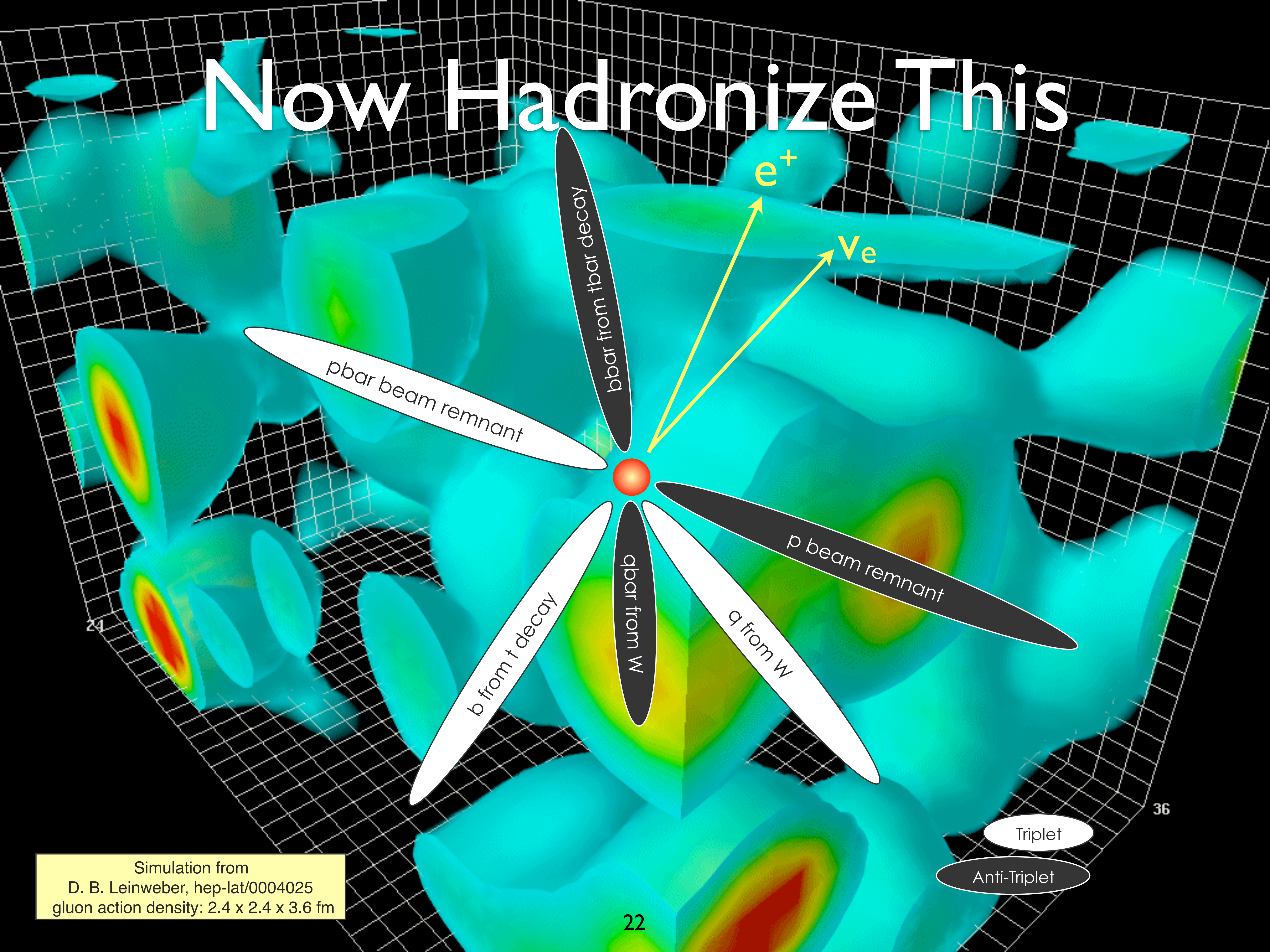

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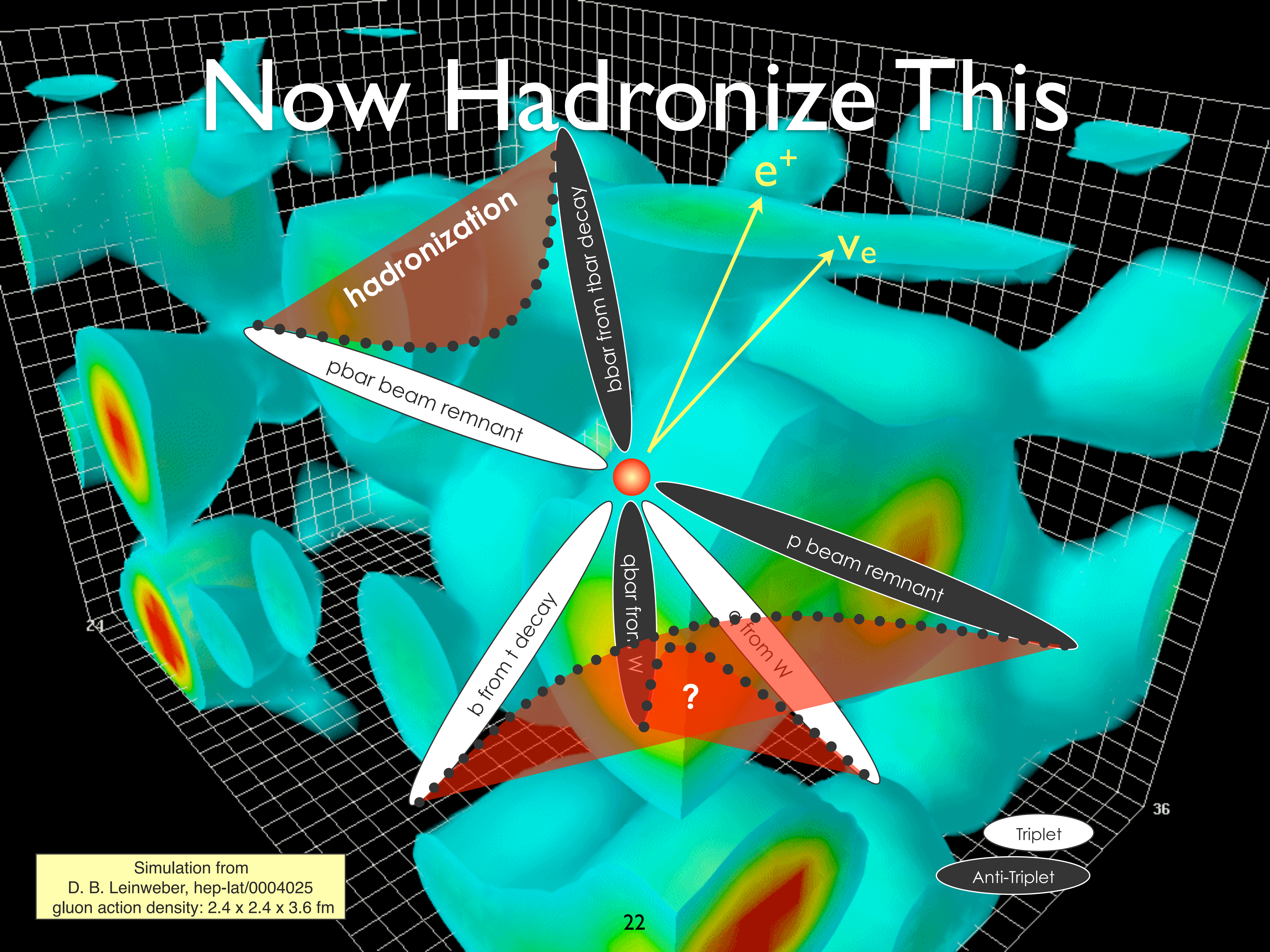

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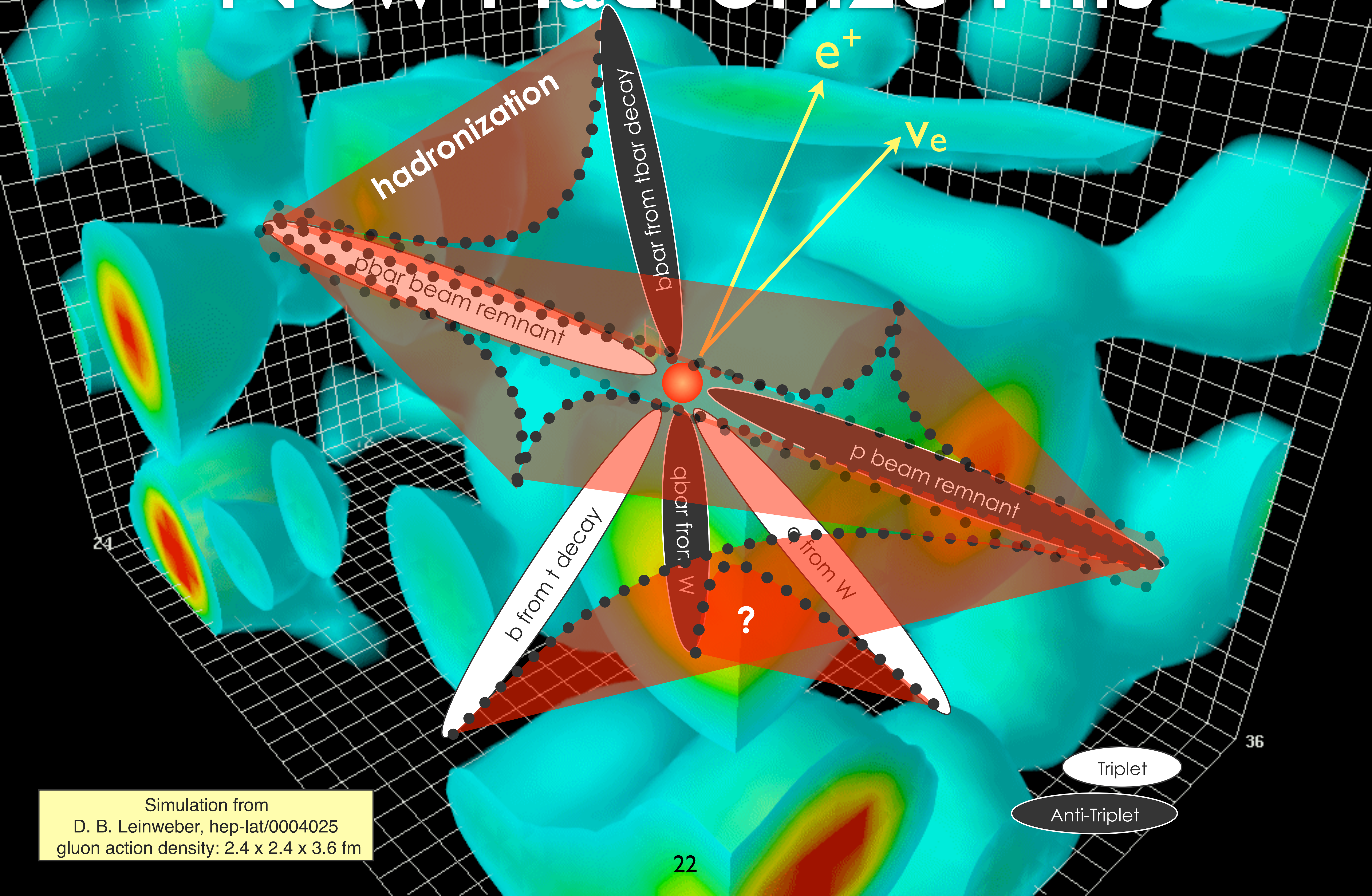

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- Given a set of partons resolved at a scale of ~ 1 GeV (the shower + MPI cutoff), need a **"mapping"** from this set onto a set of on-shell colour-singlet hadronic states.
- I.e., a fully exclusive fragmentation function defined at Q_{Had} ~ 1 GeV

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MC models do this in three steps

1. Map partons onto **continuum of highly excited hadronic states** *(called 'strings' or 'clusters')*
2. Iteratively map strings/clusters onto **discrete set of primary hadrons** *(string breaks / cluster splittings / cluster decays)*
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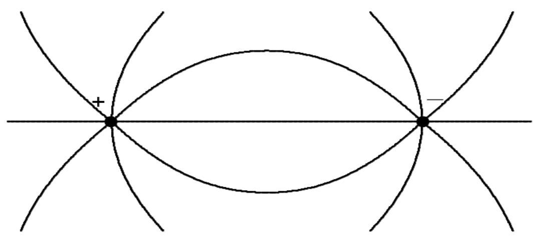
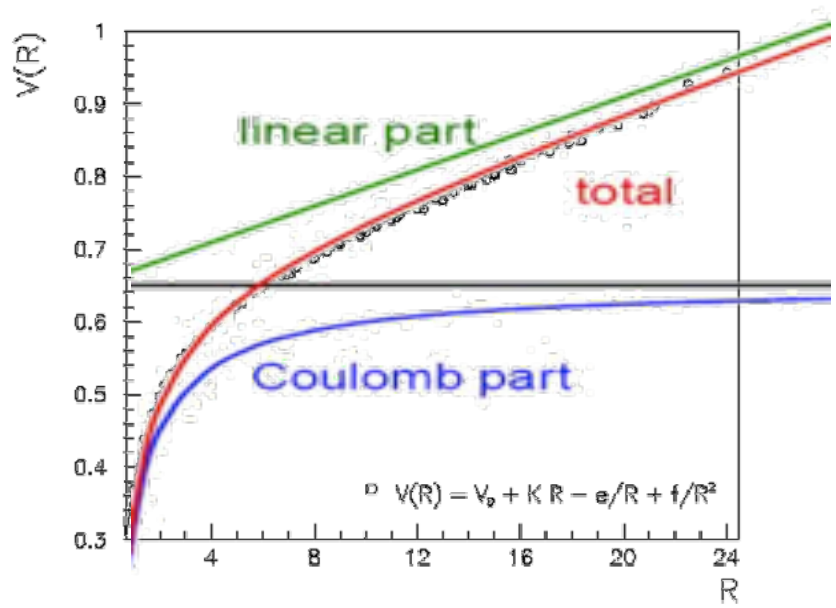
From Partons to Strings

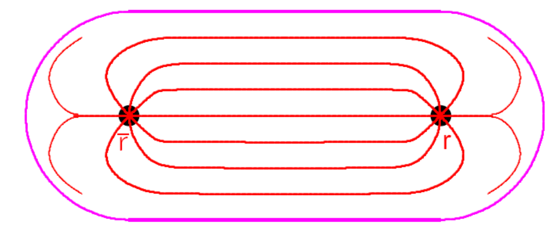
Short Distances ~ pQCD



Partons



Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

$$\boxed{F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \quad \Longleftrightarrow \quad V(r) \approx \kappa r}$$

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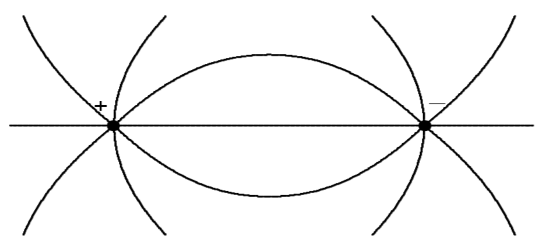

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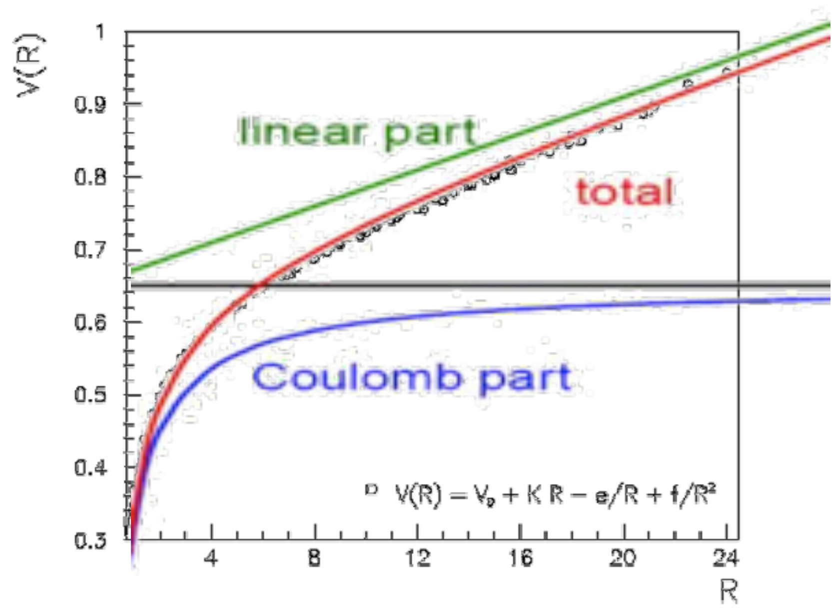

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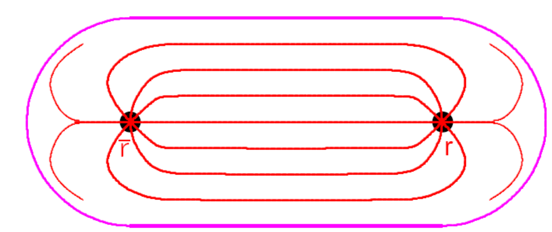

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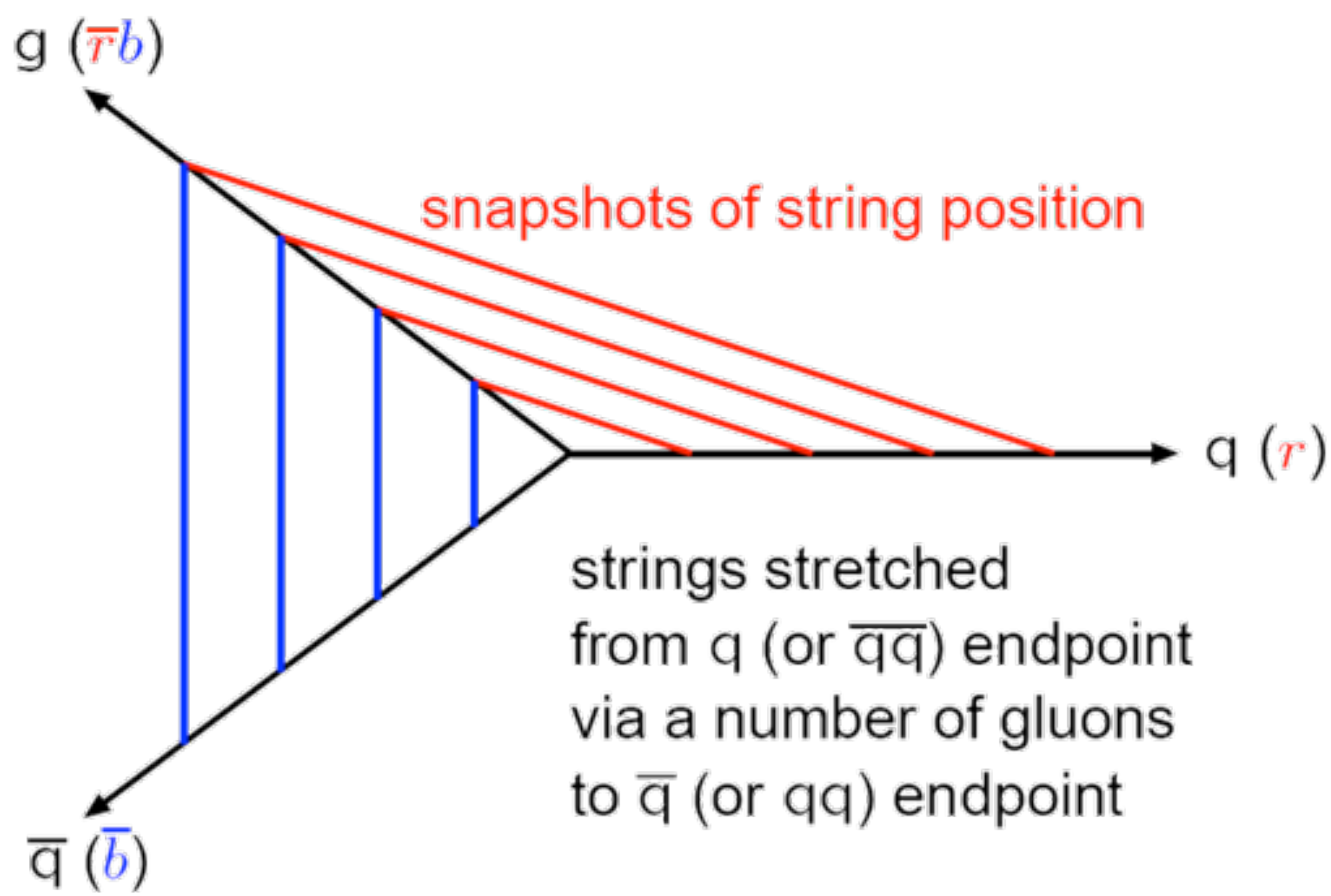
- **Motivates a model:**
  - Separation of transverse and longitudinal degrees of freedom
  - Simple description as 1+1 dimensional worldsheet – string – with Lorentz invariant formalism

The (Lund) String Model

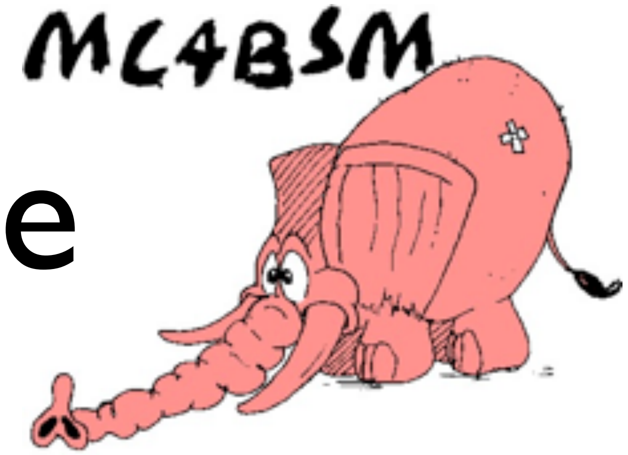
Map:

- **Quarks** > String Endpoints
- **Gluons** > Transverse Excitations (kinks)
- Physics then in terms of string worldsheet evolving in spacetime
- Probability of string break constant per unit area > **AREA LAW**



Gluon = kink on string, carrying energy and momentum

Simple space-time picture
Details of string breaks more complicated

The Way of the 

- The present state of phenomenology
  - Heavily based on semi-classical approximations
    - Leading Order, Leading Log, Leading Color, semi-classical string models
  - Sufficient to reach O(10%) accuracy (with hard work)
    - ➔ sufficient to get overall picture during first few years of LHC running

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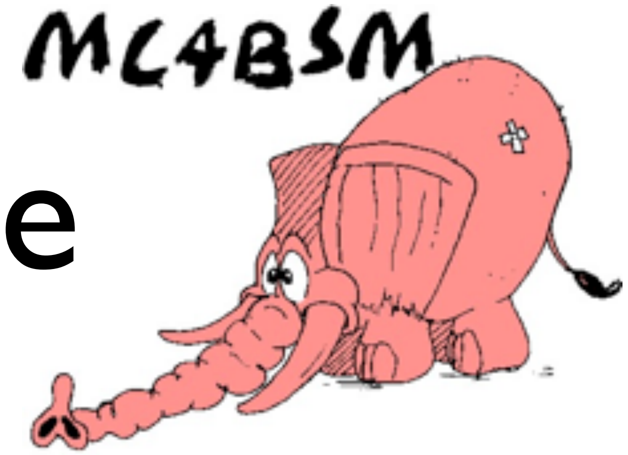

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  - Next machine is a long way off
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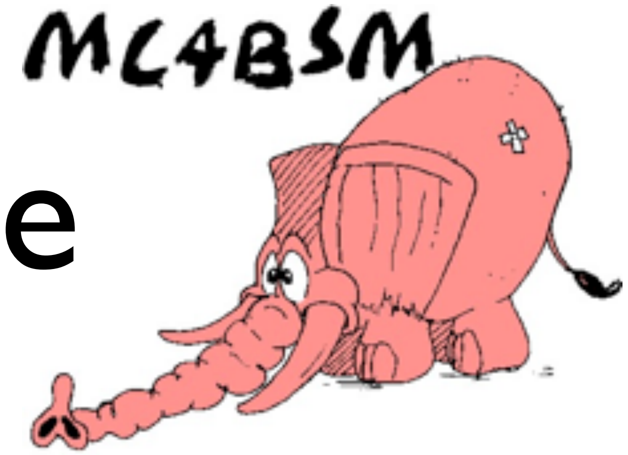
  - Gain a complete understanding of 'known' physics → PHENOMENOLOGY OF EVERYTHING (POET), such that Questions can be asked, measurements performed, with little or no limitations imposed by theoretical accuracy

The Way of the 

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- **The more immediate danger**
  - Is caused by the paradigm implied by being accustomed to events that both look like data *and* have an underlying (semi-)classical picture

The Tyranny of Carlo

J. D. Bjorken

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But it often happens that the physics simulations provided by the the MC generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data. All Monte Carlo codes come with a GIGO (garbage in, garbage out) warning label. But the GIGO warning label is just as easy for a physicist to ignore as that little message on a packet of cigarettes is for a chain smoker to ignore. I see nowadays experimental papers that claim agreement with QCD (translation: someone's simulation labeled QCD) and/or disagreement with an alternative piece of physics (translation: an unrealistic simulation), without much evidence of the inputs into those simulations."

The Tyranny of Carlo

J. D. Bjorken

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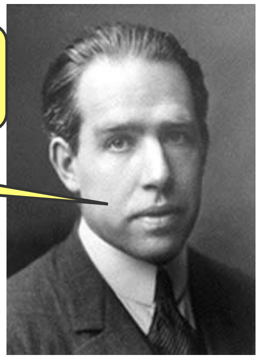
Authors: can we do better than the GIGO label? Uncertainty Bands
Users: account for parameters and report on pertinent cross-checks and validations

The Problem of Measurement

- It is tempting to correct measurements for “annoying” effects
  - Measurements are performed on long-lived / macroscopic objects which are almost classical

Correspondence: Large quantum numbers → classical



Niels Bohr (1885-1962)

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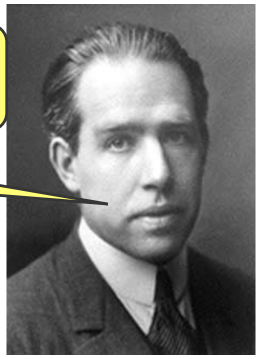

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- Theory (MC): In Resonant, Singular, and Non-Perturbative limits, quantum → semi-classical "MC truth"
  - There either *was* or *wasn't* a H / W / t / … in this event
  - Bremsstrahlung either was off *this* parton or off *that* parton
  - A string goes from *this* parton to *that* parton
  - *This* pion went over here, *that* pion went over there
- ➔ hadron-level → parton-level corrections, imagining an "LO" matrix element (with asymptotic incoming and outgoing partons) sitting the middle of a bunch of gook, etc.

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Complementarity: The wave function is subjective, and it is all you're going to get - The "underlying classical truth" does not exist (no hidden variables)

Listen to Niels!

- We need to listen to Niels! The semi-classical nature of current descriptions is formally correct, but nonetheless deceptive
  - Multi-slit experiments. Signal and background will interfere, at some level
- Quantum Interference Effects
  - Resonant: interference between resonance and background.
    - An event-by-event truth does not exist.
    - That is why SHERPA does not put a Z in the event record for Z(→hadrons)+jets.
  - Bremsstrahlung: 1st-order interference treated semi-classically (angular ordering), but assignment of radiation to this or that parton still arbitrary.
    - That is why VINCIA does not assign a unique mother for each radiated gluon
  - Non-perturbative: interference between different string/cluster topologies
    - Not accounted for in current descriptions
    - And: Color neutralization → Impossible to associate a given hadron with a given parton
  - Hadron-level: the momentum of each pion is affected by all other pions in the event (identical bosons, Bose-Einstein correlations).
    - There is no universal process-independent correction that would be infinintely precise
    - And: how long do you wait before you observe the leptons and hadrons?

A Quantum Paradigm

(for the LHC?)

Whatever you do ...
Define it in terms of
Physical Observables

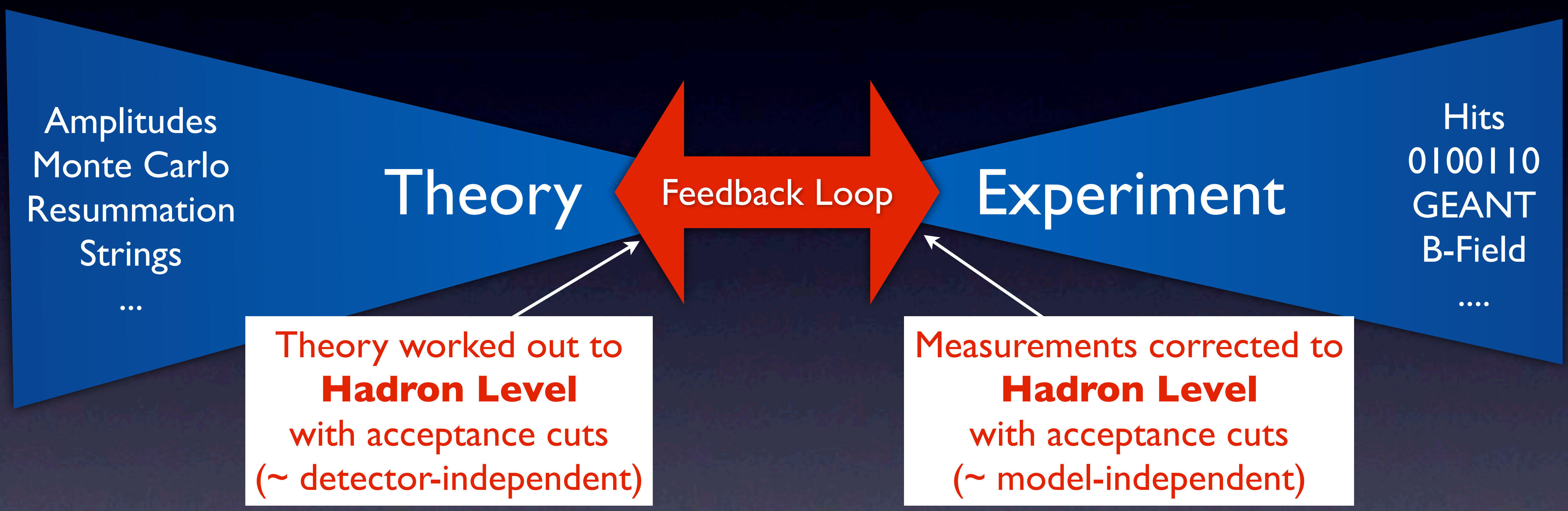
THEN
Extract fundamental
quantities from those
observables

Count what is Countable

Measure what is Measurable

(and keep working on the beam)

G. Galilei



If not worked out to hadron level: data must be unfolded with *someone else's* hadron-level theory

Unfolding beyond hadron level dilutes precision of raw data (Worst case: data unfolded to ill-defined 'MC Truth' or 'parton level')

Conclusions

- **QCD Phenomenology** is witnessing rapid evolution: ME matching, tuning, showers, interfaces ...
  - Driven by demand of high precision in complex LHC environment with huge phase space
- A true perturbative POET

  - Only uses physical observables
  - Reduces and (reliably) evaluates perturbative uncertainties
  - Can extract very high precision from inclusive measurements (high-precision frontier)
- Then focus on the really hard stuff ...
  - For which fundamentally new ideas may be needed