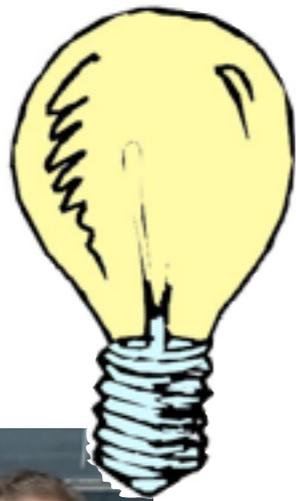


From Partons to Pions

P. Z. Skands (CERN-TH)

New Physics Pipeline

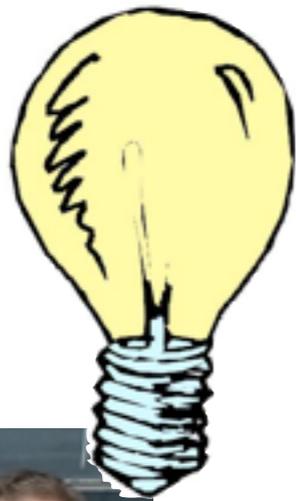
Comparisons
to Collider
observables



$L = \dots$

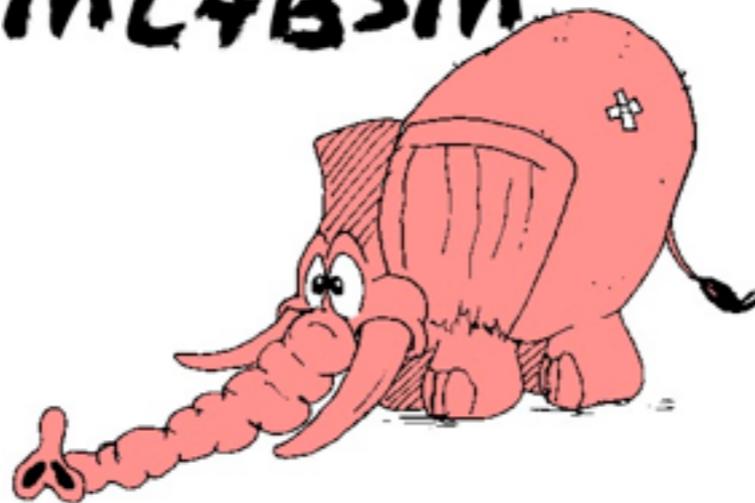
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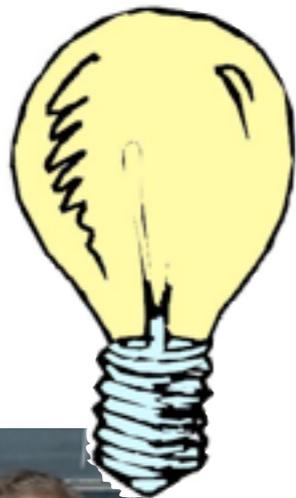
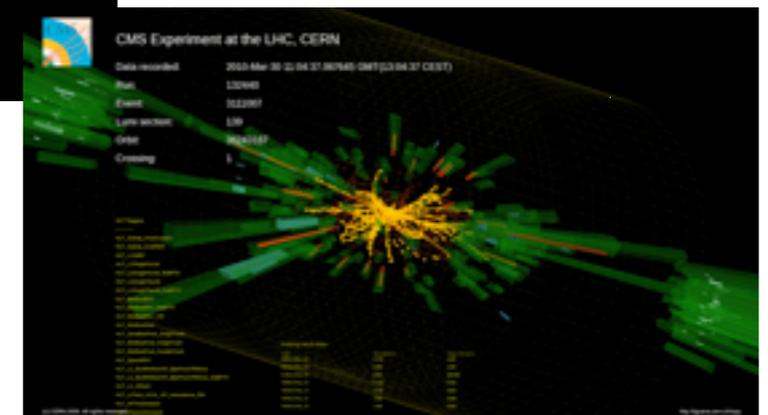
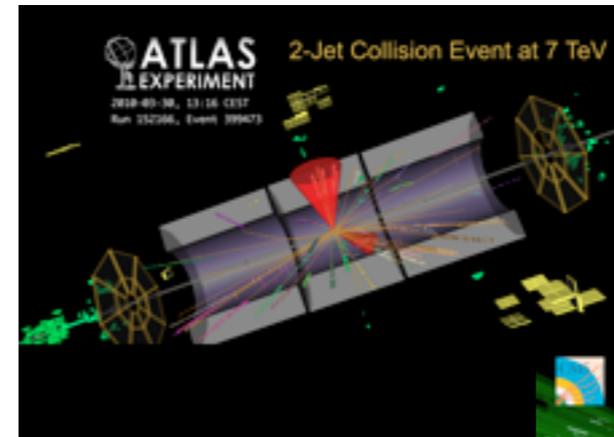
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MC4BSM



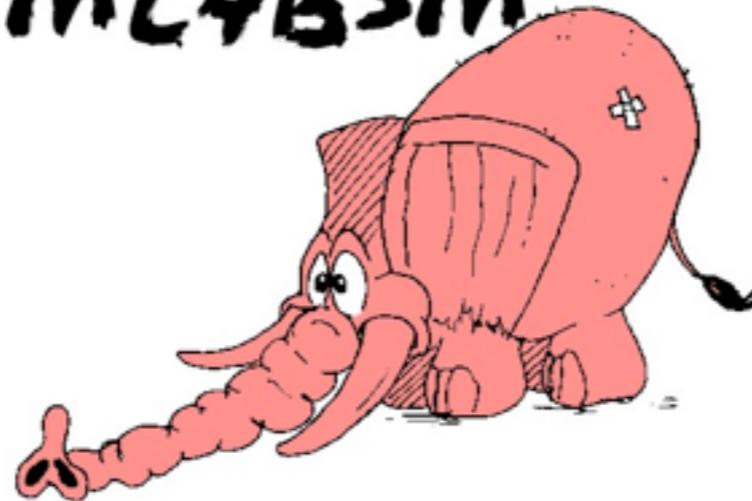
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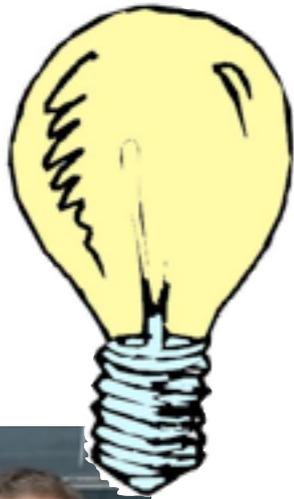
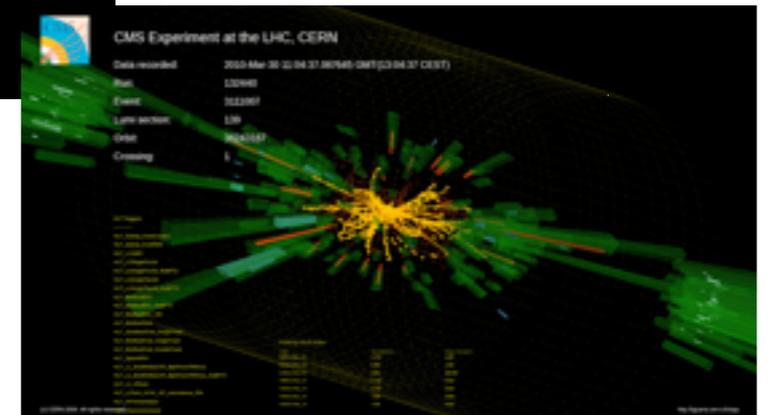
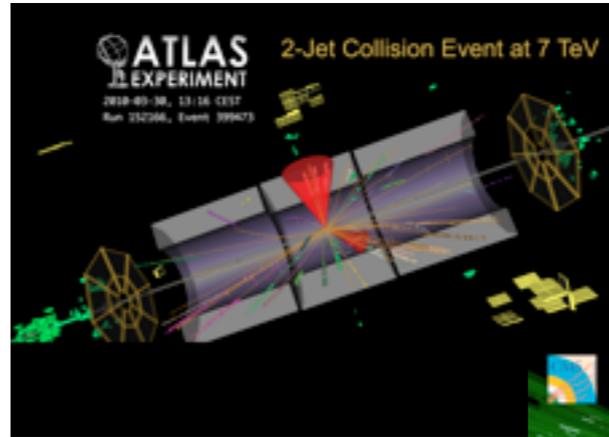
L=...

MC4BSM



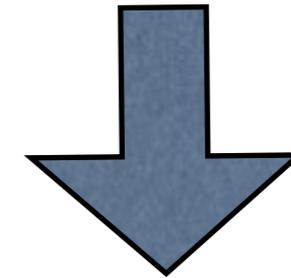
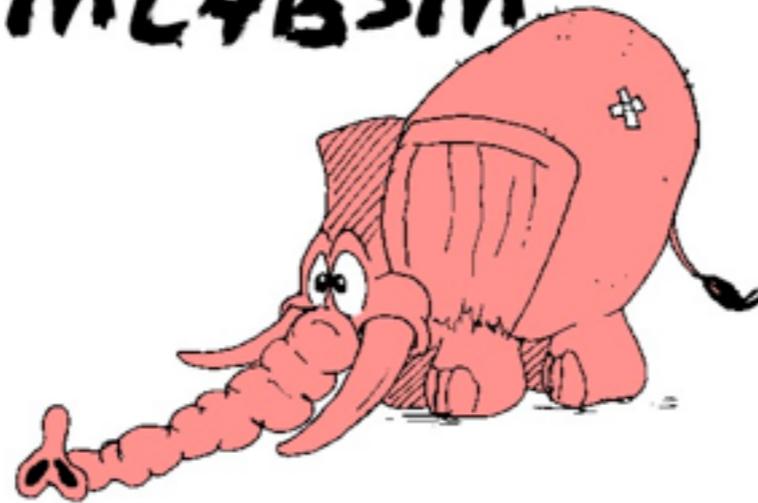
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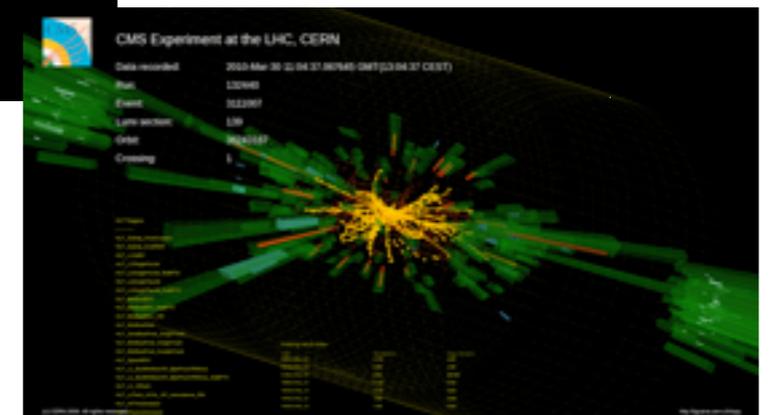
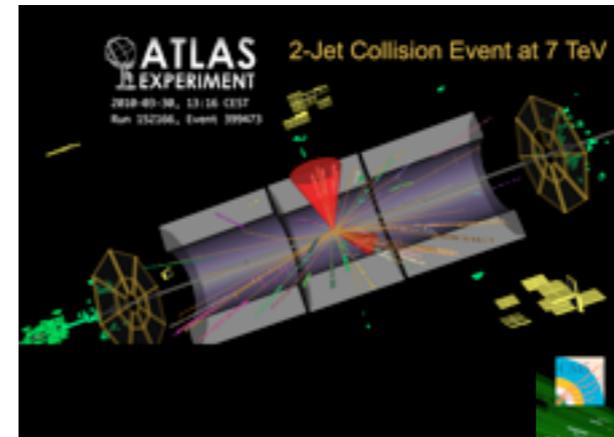
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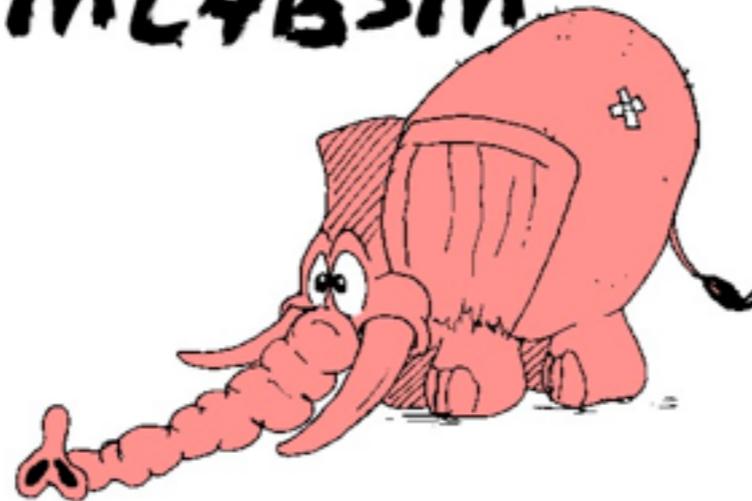
A) Model is wrong

New Physics Pipeline

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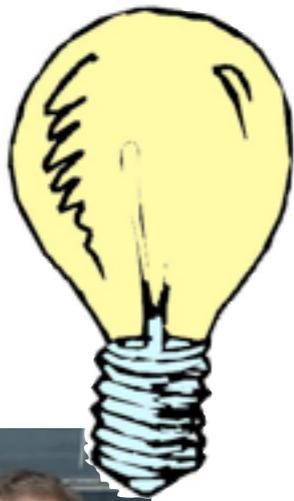
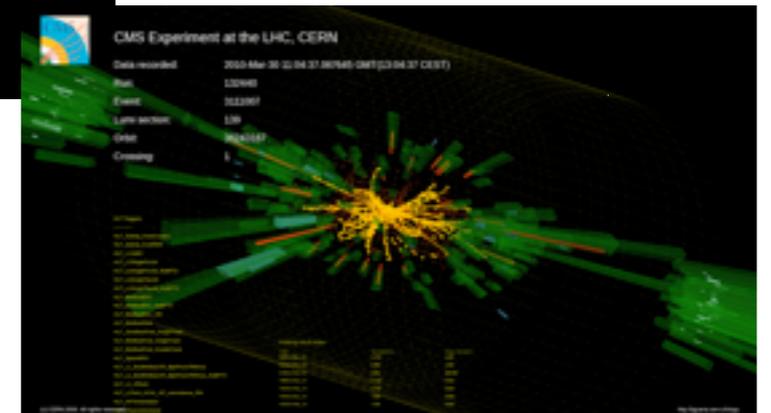
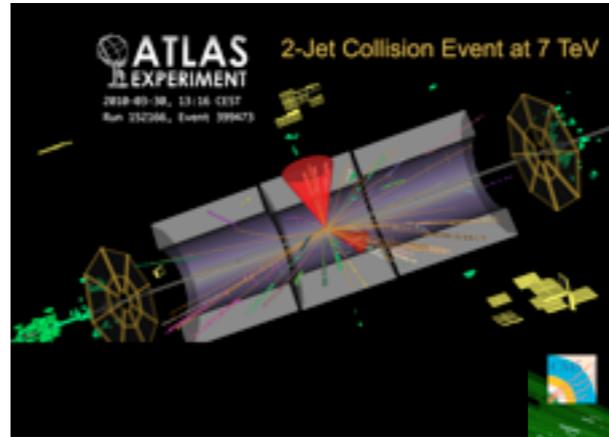


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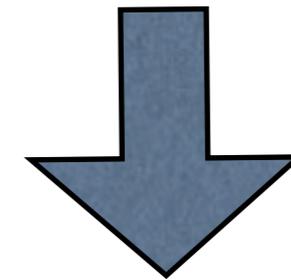
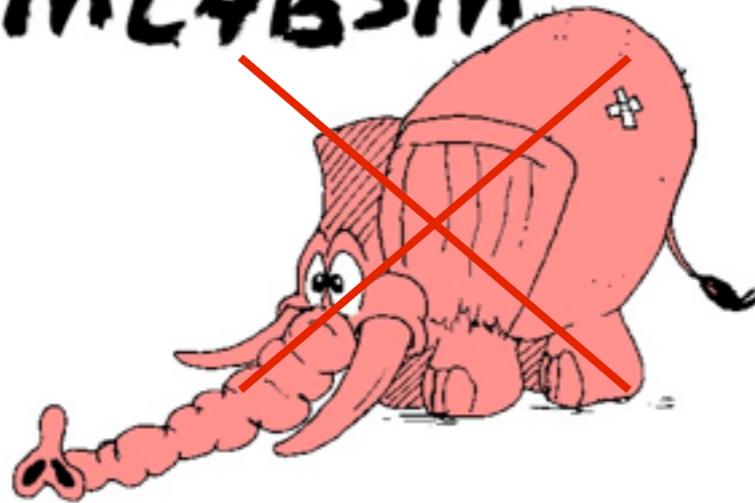
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MC4BSM



B) Monte Carlo is wrong

From Partons ...

Main Tool

Lowest-Order Matrix Elements calculated in a fixed-order perturbative expansion \rightarrow parton-parton scattering cross sections

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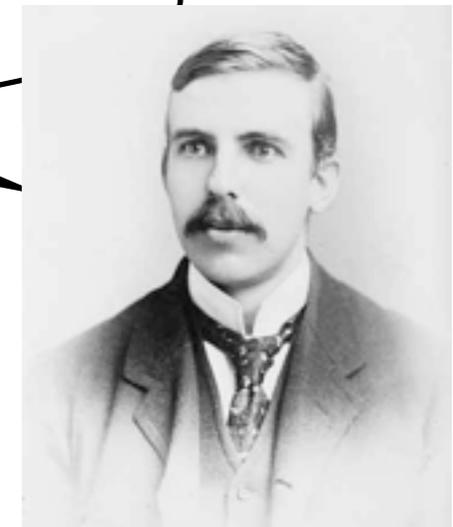
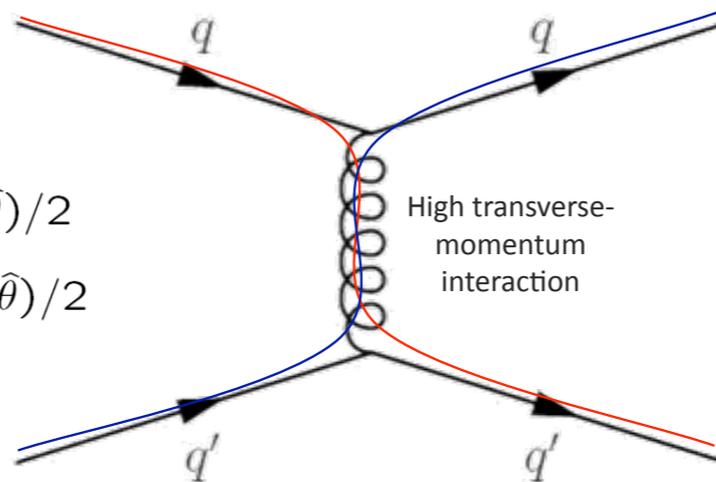


$$qq' \rightarrow qq' : \frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi}{\hat{s}^2} \frac{4}{9} \alpha_S^2 \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$$

$$\hat{s} = (p_1 + p_2)^2$$

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

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



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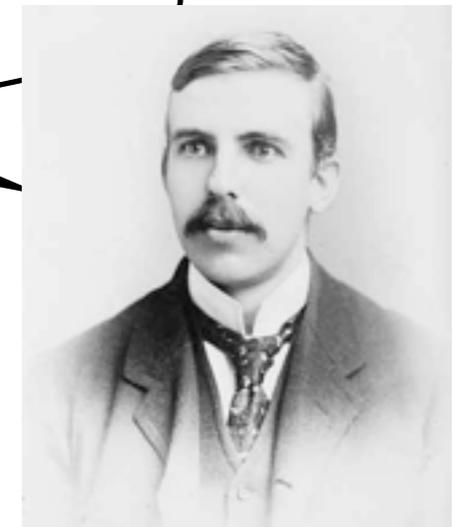
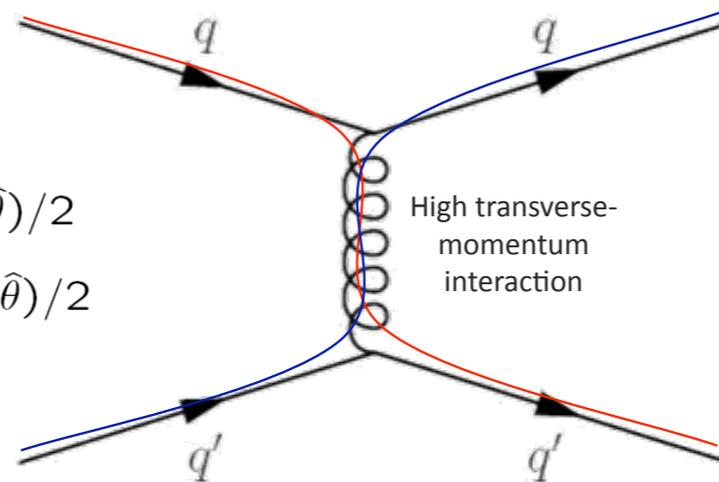
L=...

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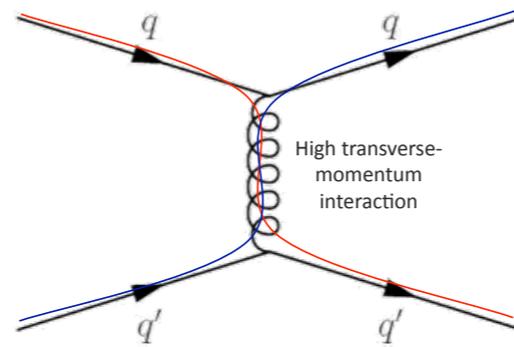
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L \rightarrow LanHEP/FeynRules \rightarrow MadGraph/CompHEP/CalcHEP/... \rightarrow partons

... to Pions



... to Pions



Reality is more complicated

Complications

LO = **Leading Order** and **Totally Inclusive**

Radiative corrections

Complications

LO = **Leading Order** and **Totally Inclusive**

Radiative corrections

- **Additional jets** change signal topology

Complications

LO = **Leading Order** and **Totally Inclusive**

Radiative corrections

- **Additional jets** change signal topology
- **K factors** change cross sections (total *and* differential)

Complications

LO = ***Perturbative*** and ***Factorized***

Hadronization, Underlying Event,
Beam Remnants, Hadron Decays, ...

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Complications

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- **No major changes** to event rates or topologies

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RGSIW KGIWUSUSI2' HSIQLOU D6CSλ2' ...

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RGSIW KGIWUSUSI? HSIQLOU DECSI? ...

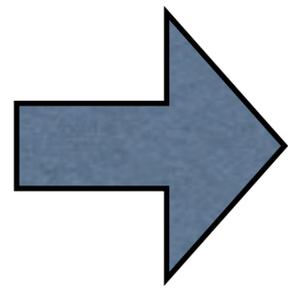
- **No major changes** to event rates or topologies
- Apparatus > 1 fm away from interaction point
- Important for **calibration** and **precision**
- **Observables** should be **physical and IR safe**

➔ The Way of the Chicken

▶ Who needs QCD? I'll use leptons

- Sum inclusively over all QCD
 - Leptons almost IR safe by definition
 - WIMP-type DM, Z' , EWSB → may get some leptons



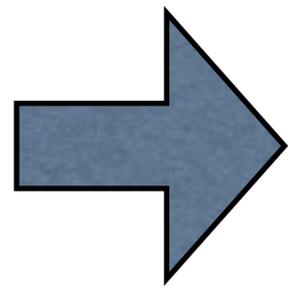


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 - High precision = higher orders \rightarrow enter QCD (and more QED)
- Isolation \rightarrow indirect sensitivity to QCD
- Fakes \rightarrow indirect sensitivity to QCD



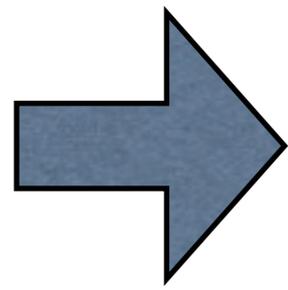


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► The unlucky chicken

- Put all its eggs in one basket and didn't solve QCD

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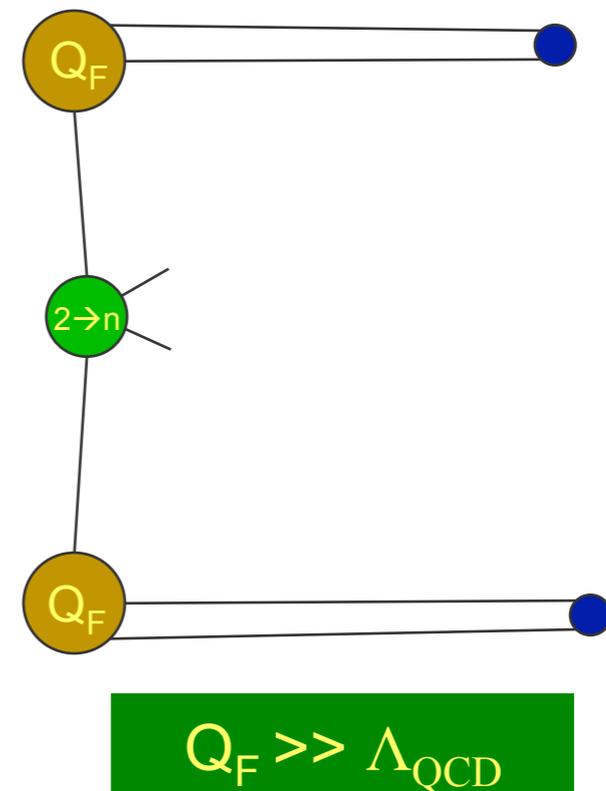
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Additional Sources of Particle Production

► Starting point: Matrix Elements

*n = a handful
+ resonance
decays*

2 → n hard parton scattering at (N)LO



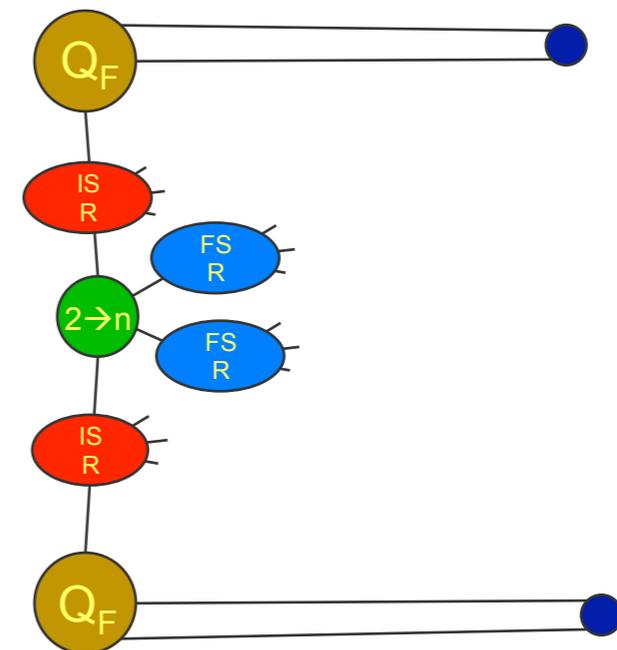
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$2 \rightarrow n$ hard parton scattering at (N)LO

+ Bremsstrahlung $\rightarrow 2 \rightarrow \infty$ at (N)LL



$$Q_F \gg \Lambda_{QCD}$$

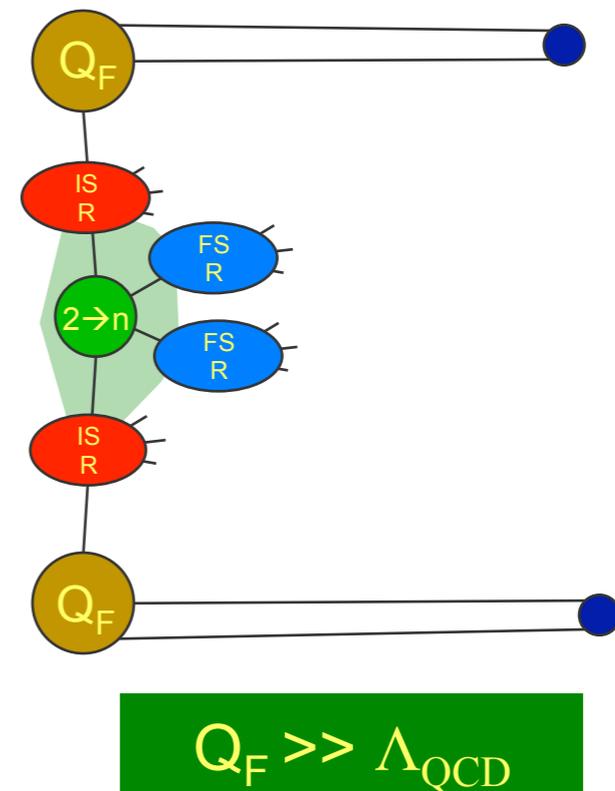
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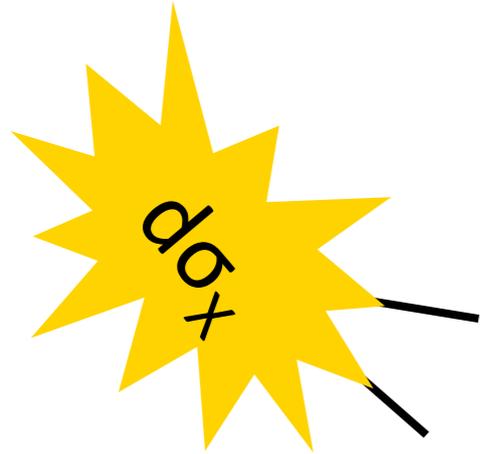
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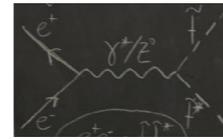
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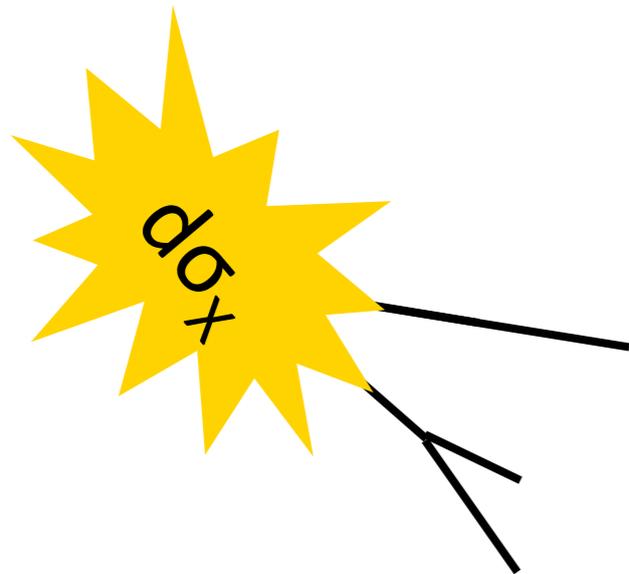
Bremsstrahlung



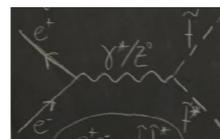
$$d\sigma_x = \dots$$



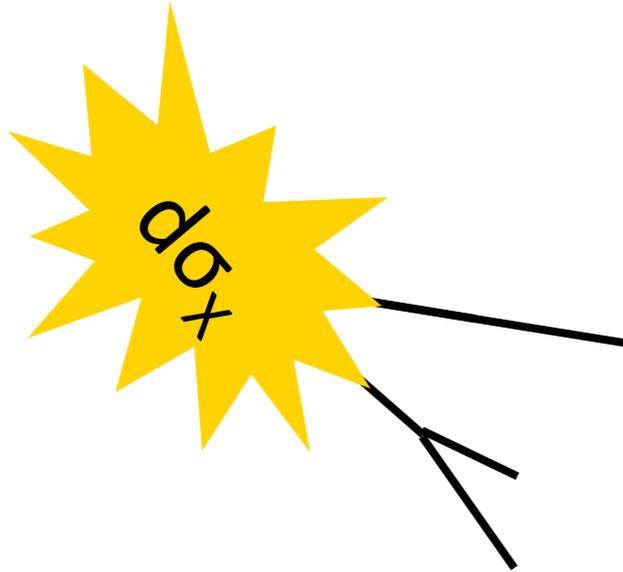
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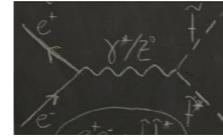
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Bremsstrahlung



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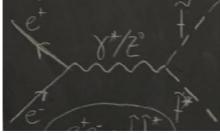


$$d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}}$$

Bremsstrahlung



“DLA” $\frac{\alpha s_{ab}}{s_{ai}s_{ib}}$

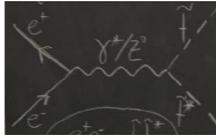
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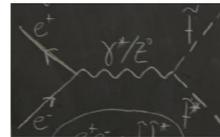
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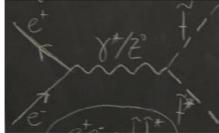
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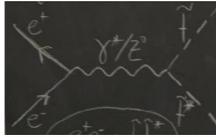
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Interpretation: the structure evolves

But something's not right...

Bremsstrahlung



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

Bremsstrahlung



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KLN

Interpretation: the structure evolves

+ UNITARITY:
 $\text{Virt} = - \text{Int}(\text{Tree}) + F$
 (or: given a jet definition, an event has either 0, 1, 2, or n jets)

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

Bremsstrahlung



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KLN

Interpretation: the structure evolves

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

This includes both real and virtual corrections

+ UNITARITY:
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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)
Run generator for ... (+ shower)
Combine everything into one sample

Matching

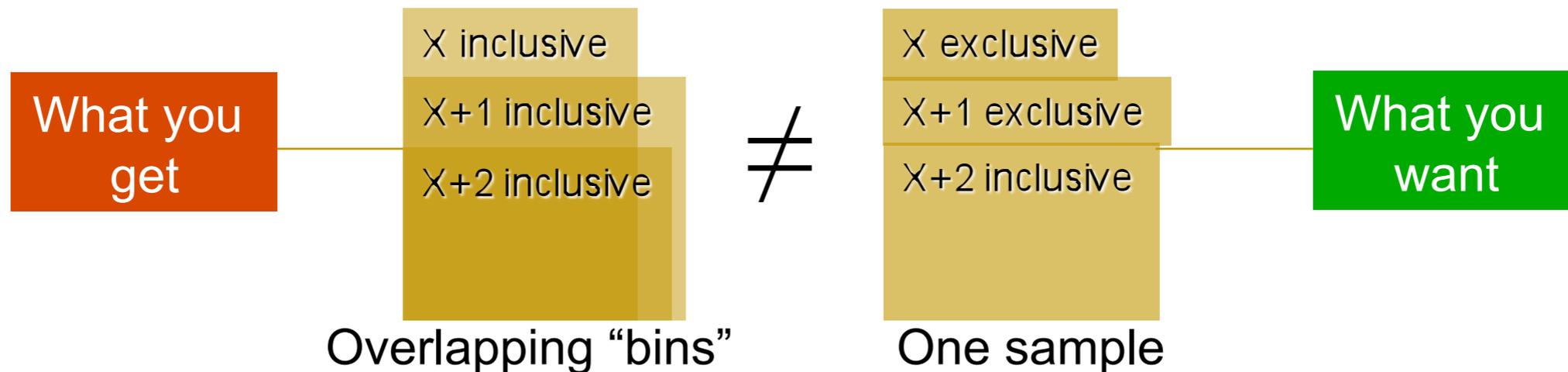
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Combine everything into one sample

► 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 $X+n$

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

• Adding back full ME
for $X+n$ would be
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Solution I: “Additive” (most widespread)

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

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Solution I: “Additive” (most widespread)

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Add event samples, with modified weights

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

$$w_{X+1} = |M_{X+1}|^2 - \textit{Shower}\{w_X\} \quad + \textit{Shower}$$

$$w_{X+n} = |M_{X+n}|^2 - \textit{Shower}\{w_X, w_{X+1}, \dots, w_{X+n-1}\} \quad + \textit{Shower}$$

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)

CKKW (SHERPA & others), MLM (ALPGEN & others): for all $X+n$ @ LO
(force Shower = 0 above “matching scale” and only match to matrix elements in that region)

The Matching Game

• Shower off X
already contains LL
part of all $X+n$

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

• Adding back full ME
for $X+n$ would be
overkill



Solution 2: “Multiplicative”

Sjöstrand, PLB185(1987)435
+ a few more recent ...

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One event sample

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

Make a “course correction” to the shower at each order

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

$$R_{X+n} = |M_{X+n}|^2 / \textit{Shower}\{w_{X+n-1}\} \quad + \textit{Shower}$$

PYTHIA: for $X+1$ @ LO (for color-singlet production and ~ all SM and BSM decay processes)

POWHEG: for $X+1$ @ LO and X @ NLO (note: positive weights)

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 (& NⁿLL?) →

Reduced Dependence

(systematic reduction of uncertainty)

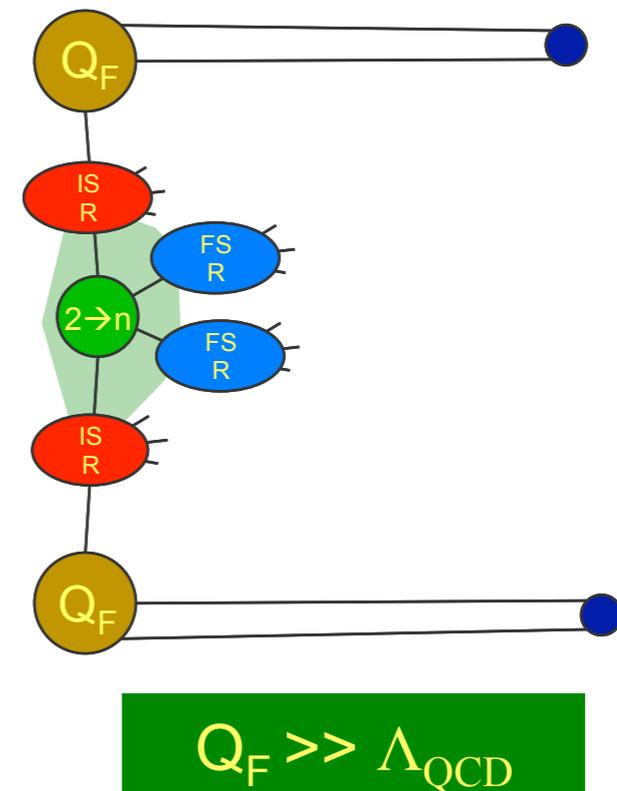
Additional Sources of Particle Production

► Starting point: Matrix Elements + Parton Showers

*n = a handful
+ resonance
decays*

$2 \rightarrow n$ hard parton scattering at (N)LO

+ Bremsstrahlung $\rightarrow 2 \rightarrow \infty$ at (N)LL



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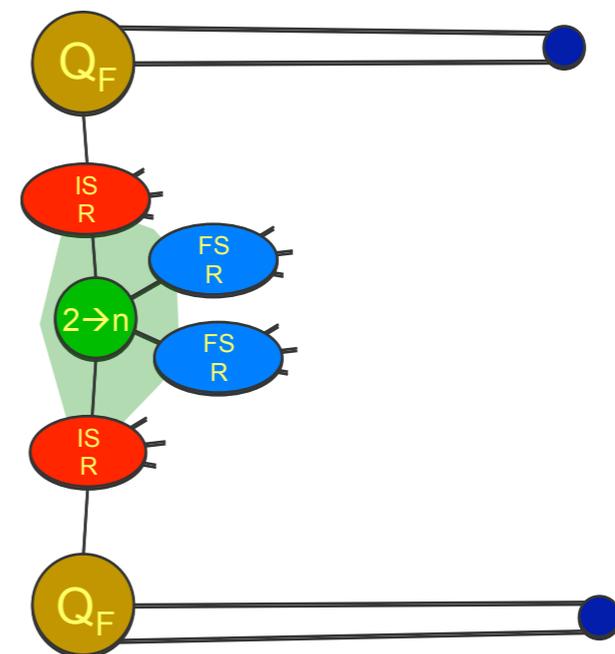
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Hadrons are not elementary
+ QCD diverges at low p_T

→ multiple perturbative parton-parton interactions

e.g. 4 → 4, 3 → 3, 3 → 2



$Q_F \gg \Lambda_{\text{QCD}}$

Underlying Event has perturbative part!

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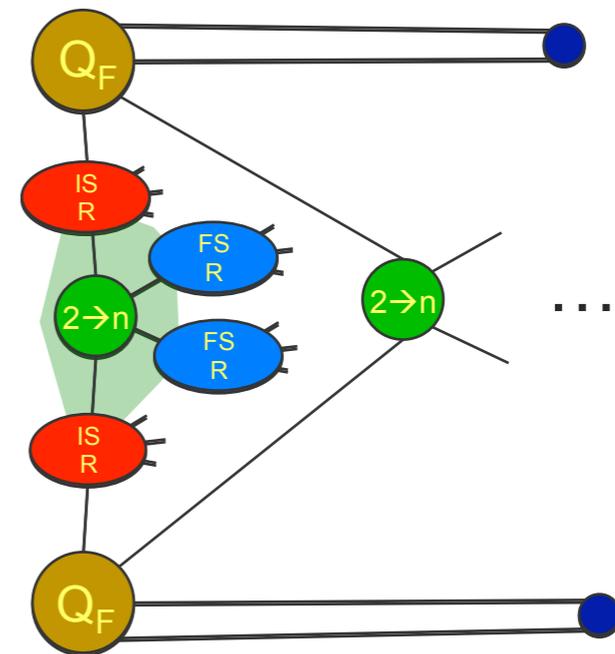
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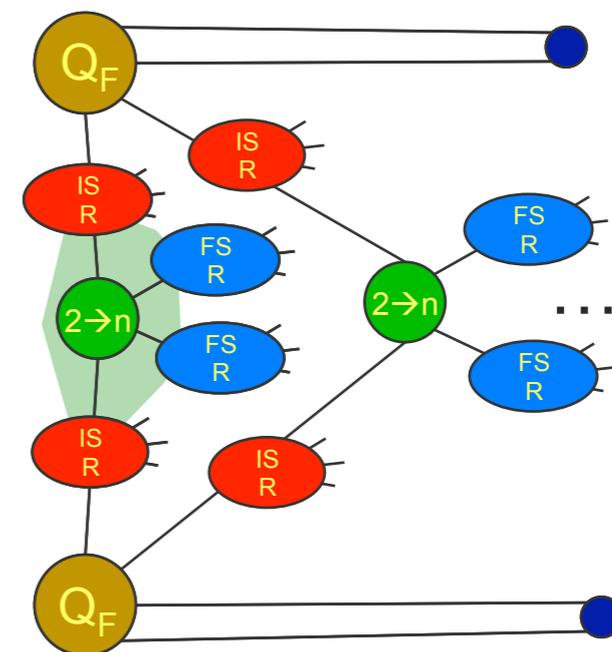
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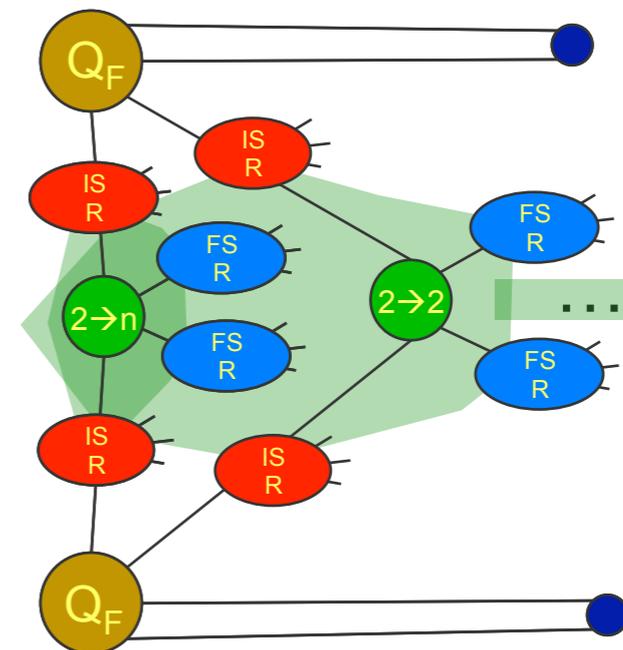
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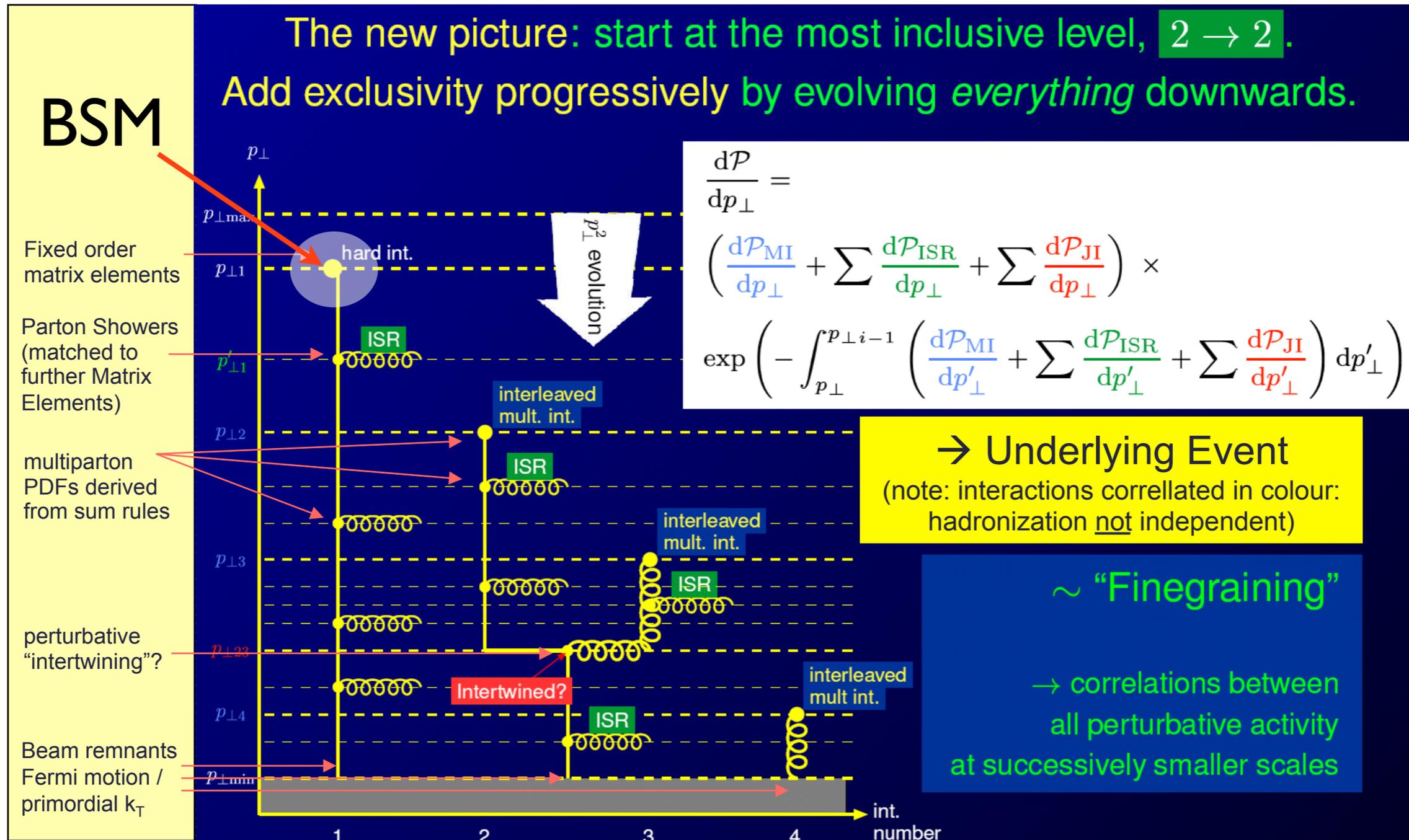
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Underlying Event: The Interleaved Idea

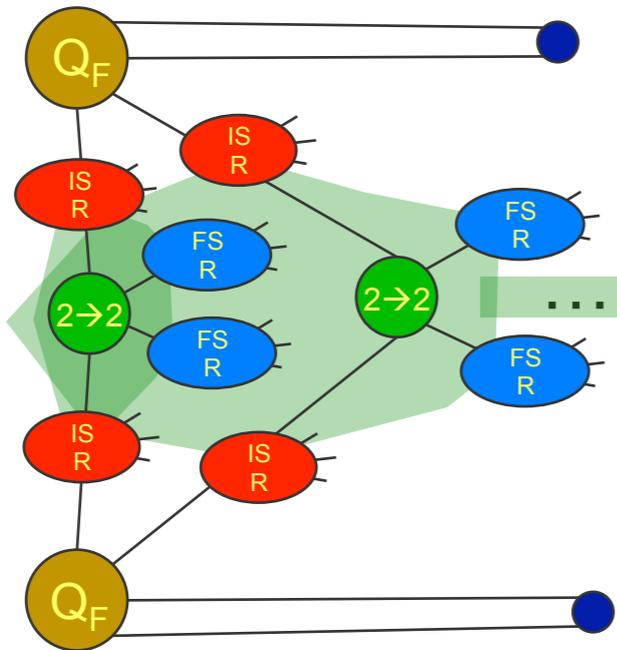


Sjöstrand & PS : JHEP03(2004)053, EPJC39(2005)129

Additional Sources of Particle Production

$Q_F \gg \Lambda_{\text{QCD}}$
 ME+ISR/FSR
 + perturbative MPI

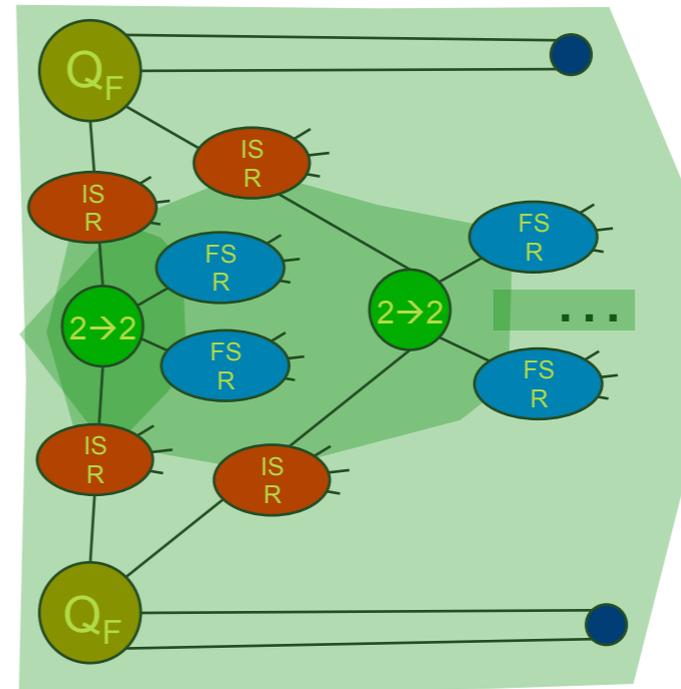
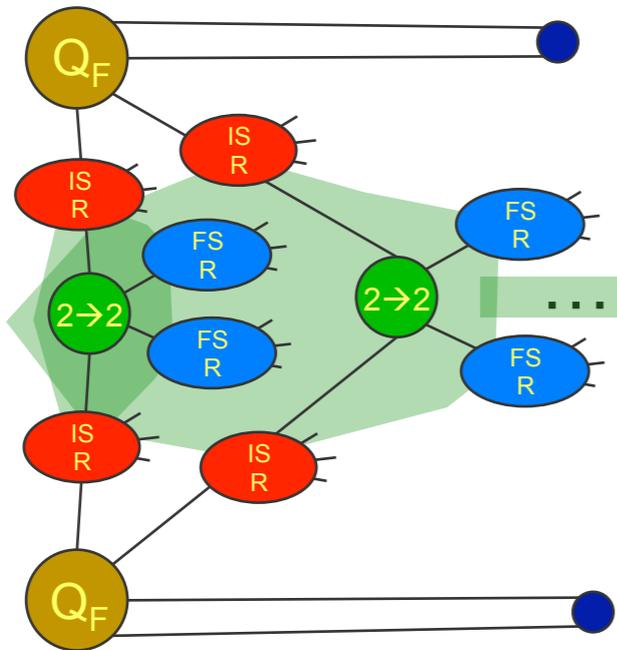
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 ME+ISR/FSR
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+
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 $Q_F \sim \Lambda_{\text{QCD}}$



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

Now Hadronize This

pbar beam remnant

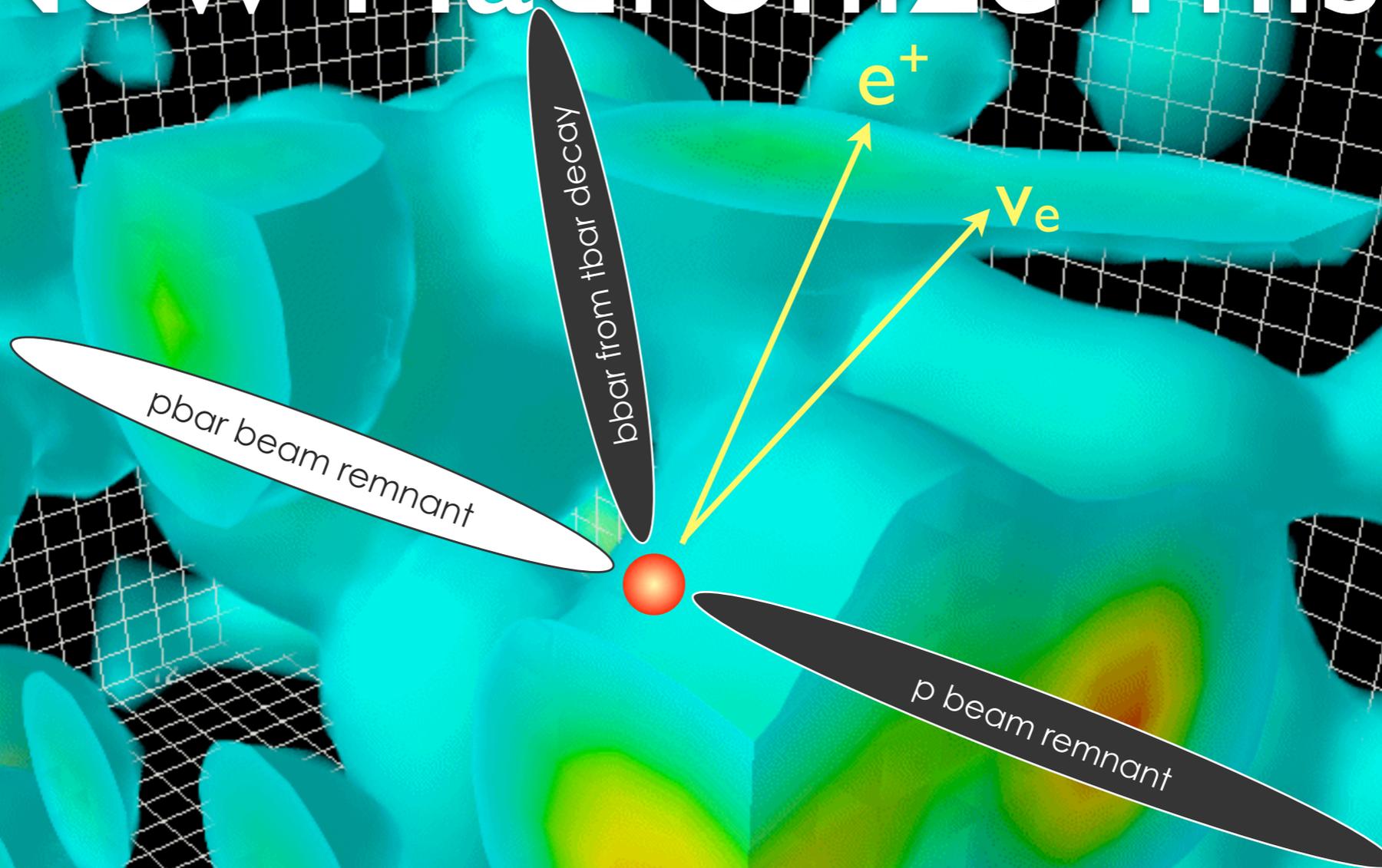
p beam remnant

Triplet

Anti-Triplet

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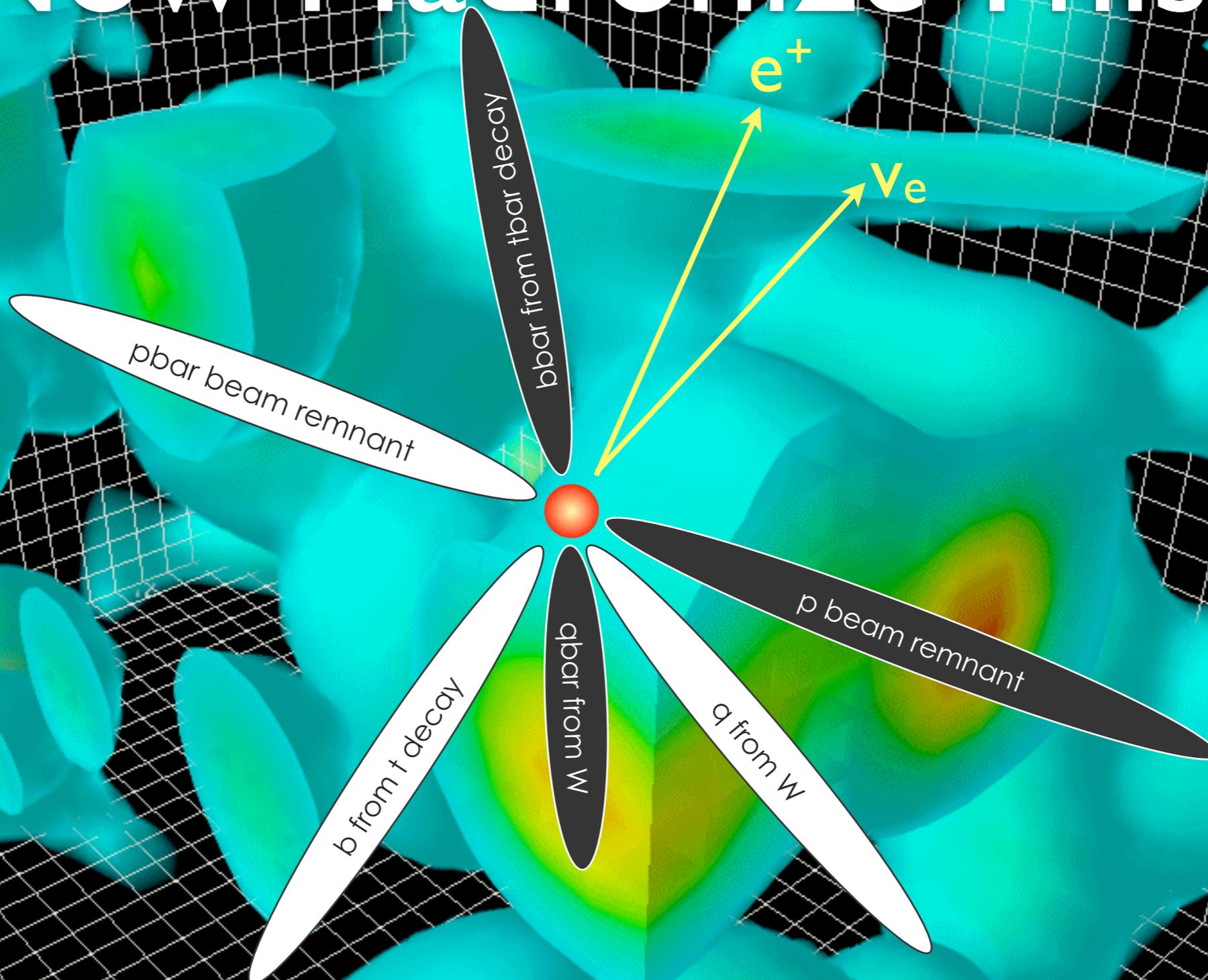


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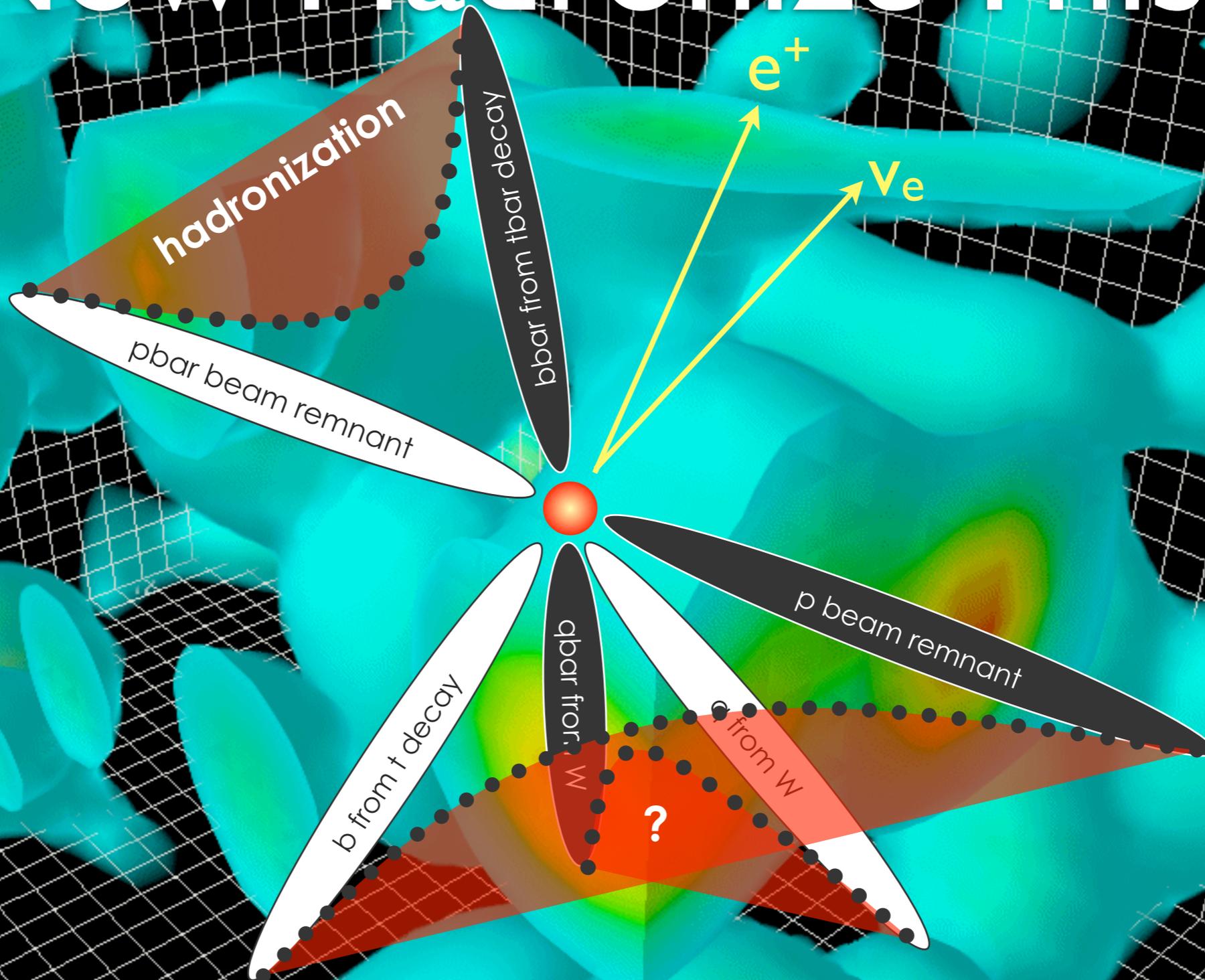
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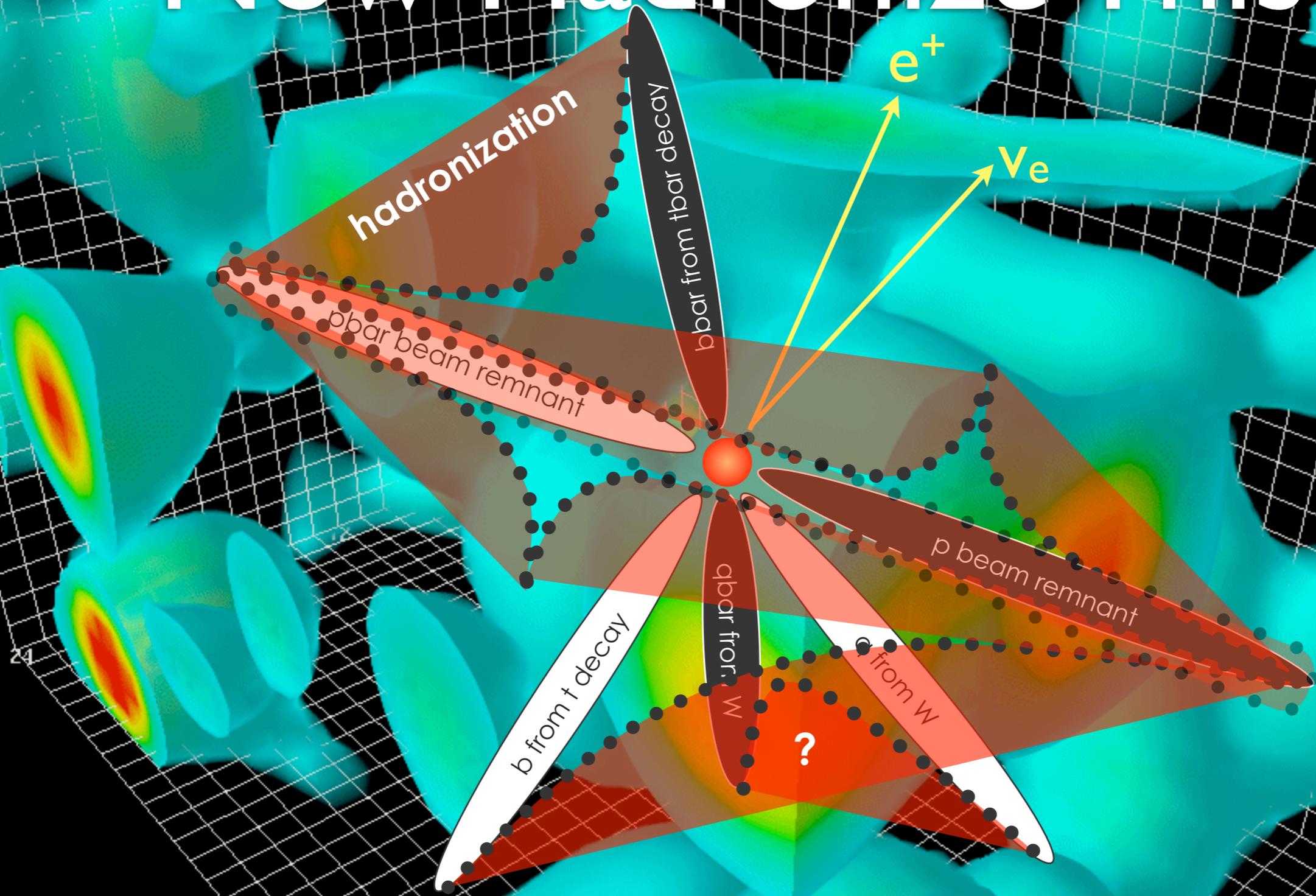
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hadronization

$p\bar{p}$ beam remnant

remnant

e^+

e^-

Triplet

Anti-Triplet

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Hadronization

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The problem:

- 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 $Q_{\text{Had}} \sim 1$ 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)
3. Sequential decays into **secondary hadrons** (e.g., $\rho \rightarrow \pi \pi$, $\Lambda \rightarrow n \pi^0$, $\pi^0 \rightarrow \gamma \gamma$, ...)

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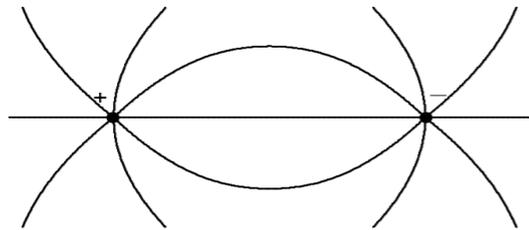
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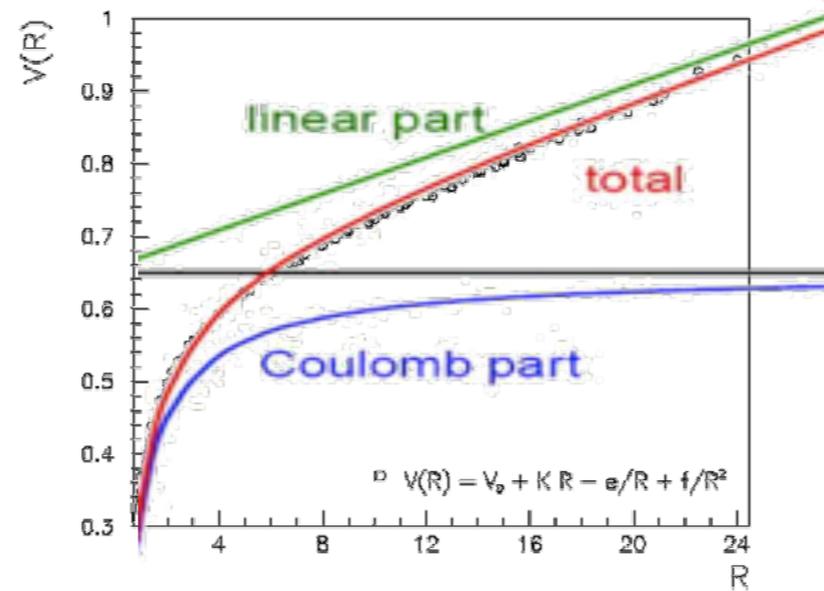
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From Partons to Strings

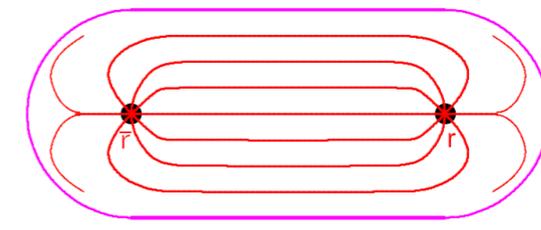
Short Distances ~ pQCD



Partons



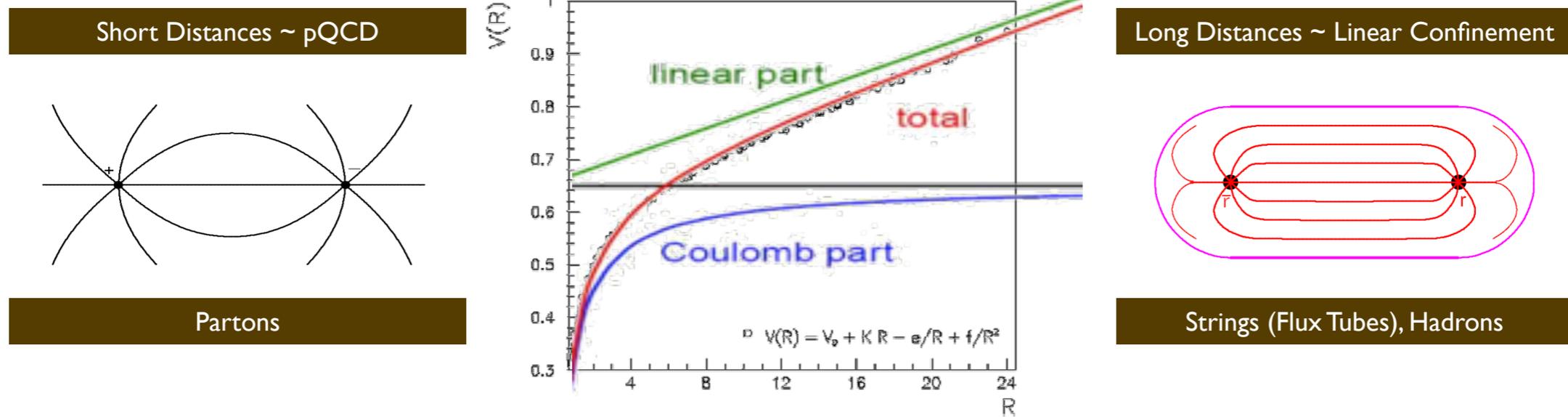
Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

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

From Partons to Strings



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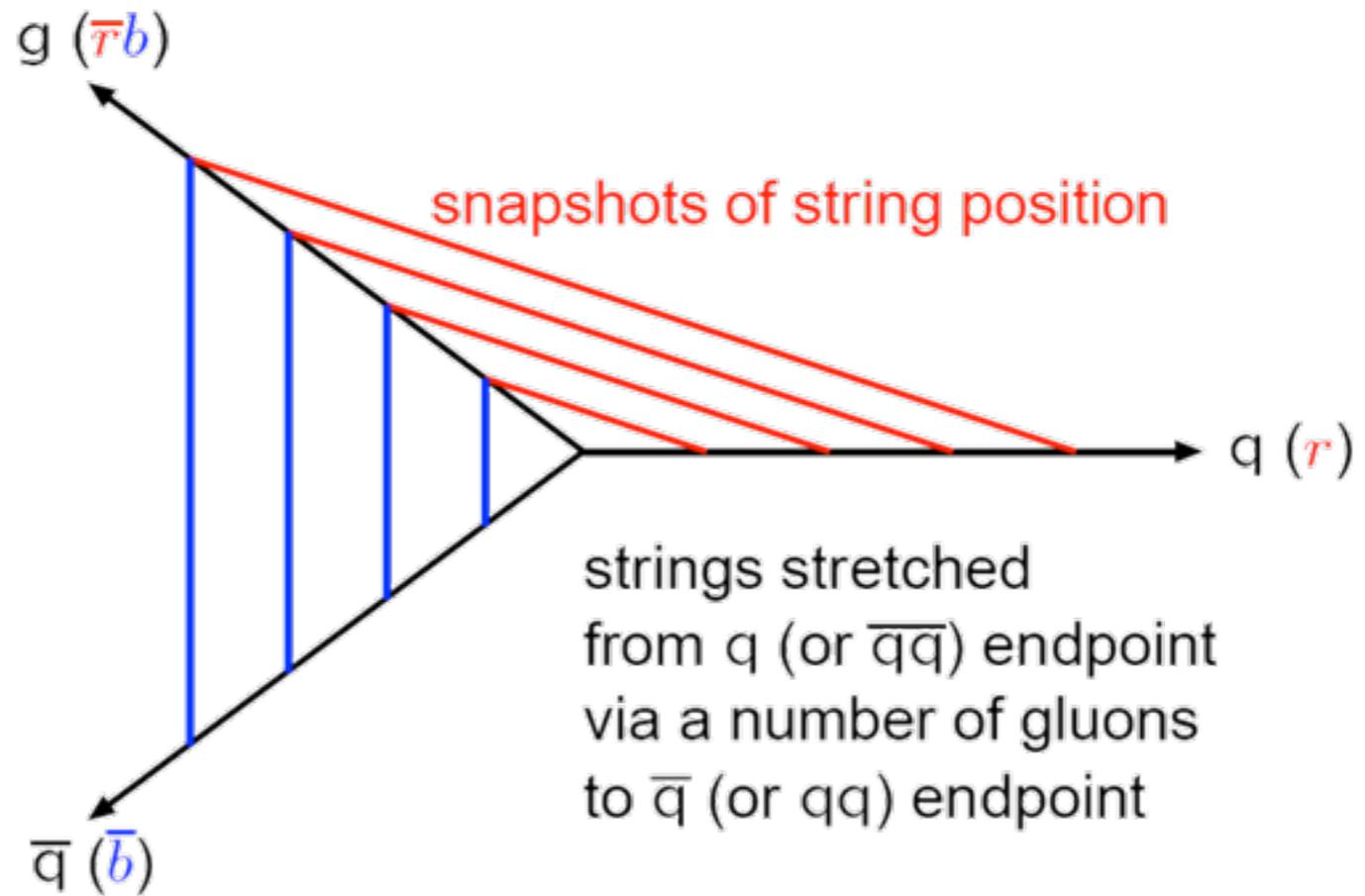
- **Motivates a model:**

- 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 ...

Outlook

Collider Physics is witnessing rapid evolution: NLO, ME matching, tuning, showers, PDFs, interfaces ...

- **Driven by demand** of high precision in complex LHC environment with huge phase space
- **Currently heavily based** on semi-classical approximations (Leading Order, Leading Log, Leading Color, ...)
 - Sufficient to reach **O(10%)** precision (with hard work)

Race to Develop a Phenomenology Of Every Thing (*POET*)

- Matching to LO, NLO, NLL, ... and (reliable) evaluations of remaining **perturbative uncertainties**
- Could then extract very **high precision** from inclusive measurements with confidence (high-precision frontier)

Then focus on the really hard stuff ...

- For which fundamentally new ideas may be needed

A Quantum Paradigm

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

THEN
Extract fundamental
quantities from those
observables