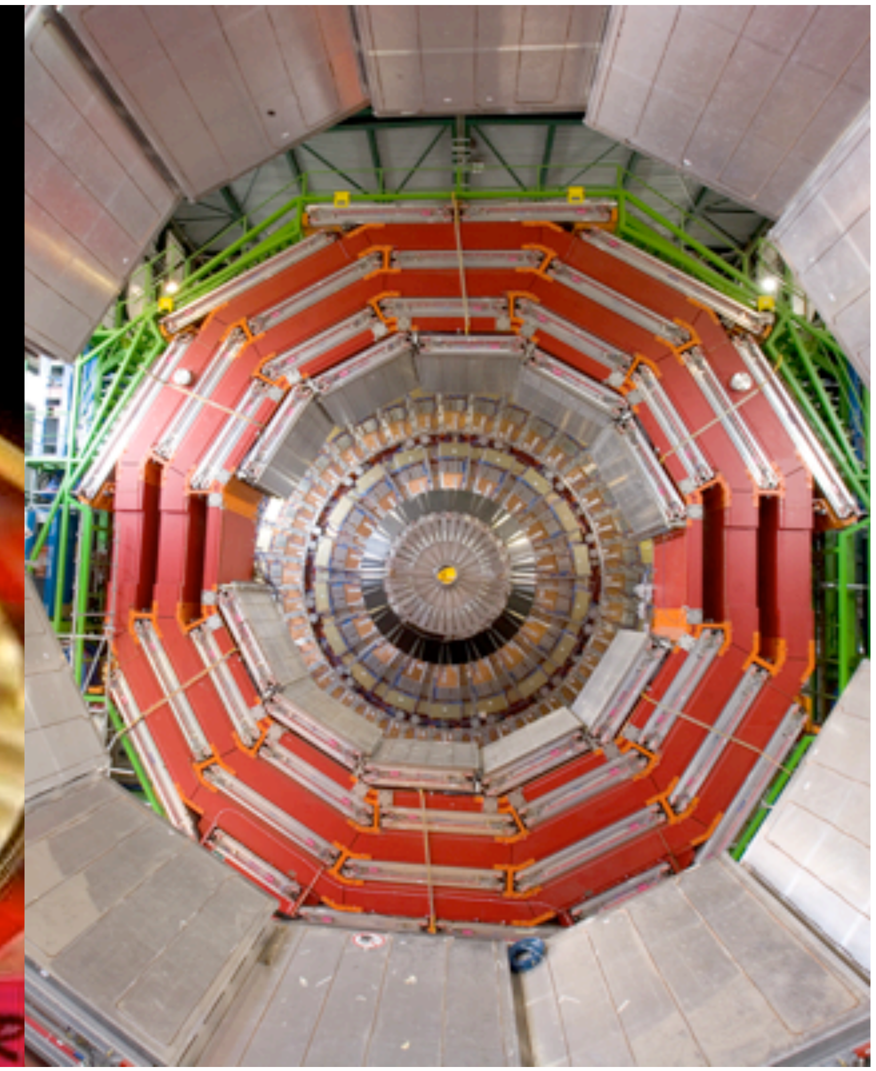
6th MC for BSM Workshop, Cornell, Ithaca, March 2012

MC Overview

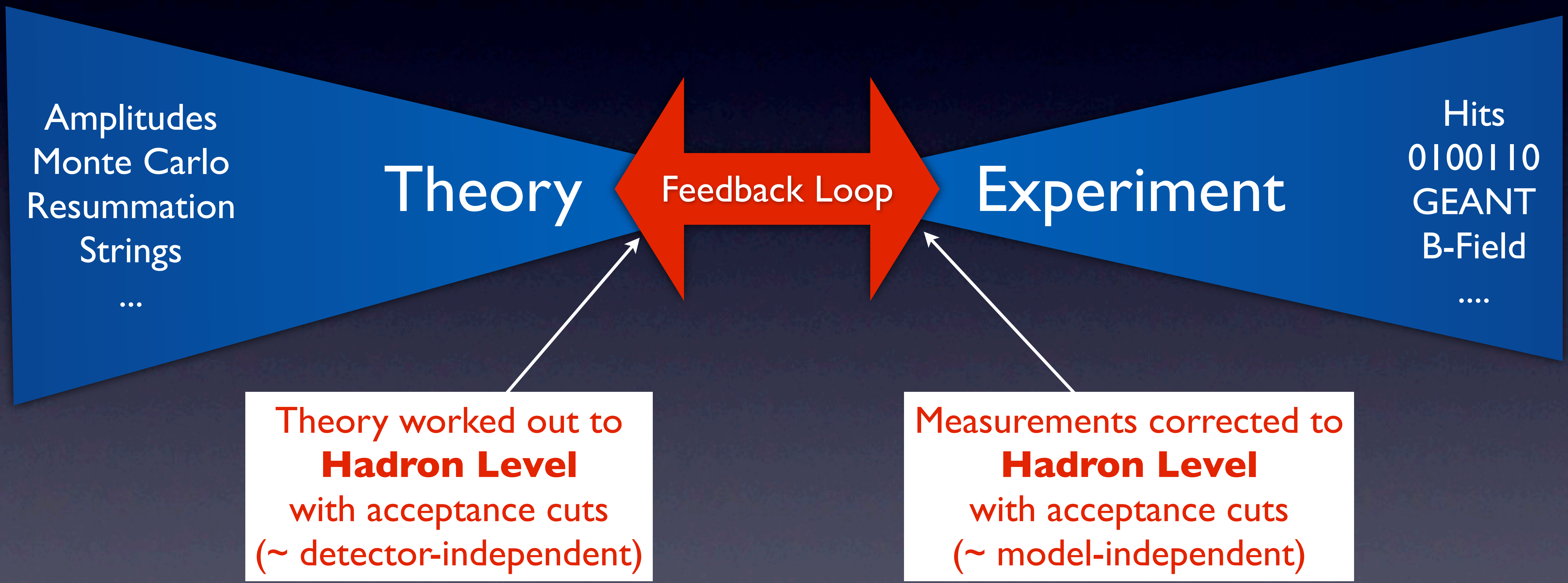



Peter Skands
(CERN-TH)

Count what is Countable

Measure what is Measurable

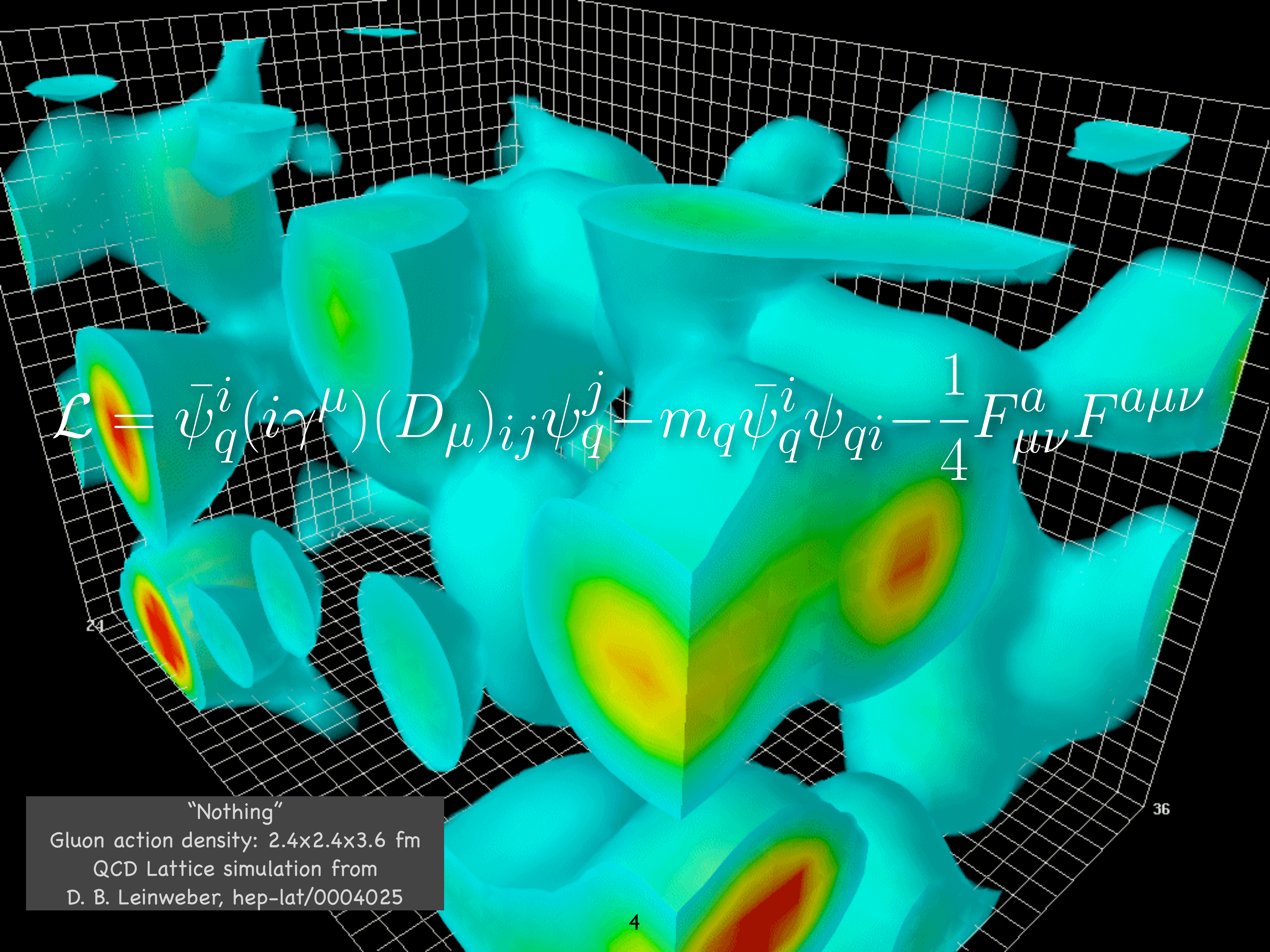
(and keep working up the beam)



THEORY

$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}$$

+ quark masses and value of α_s



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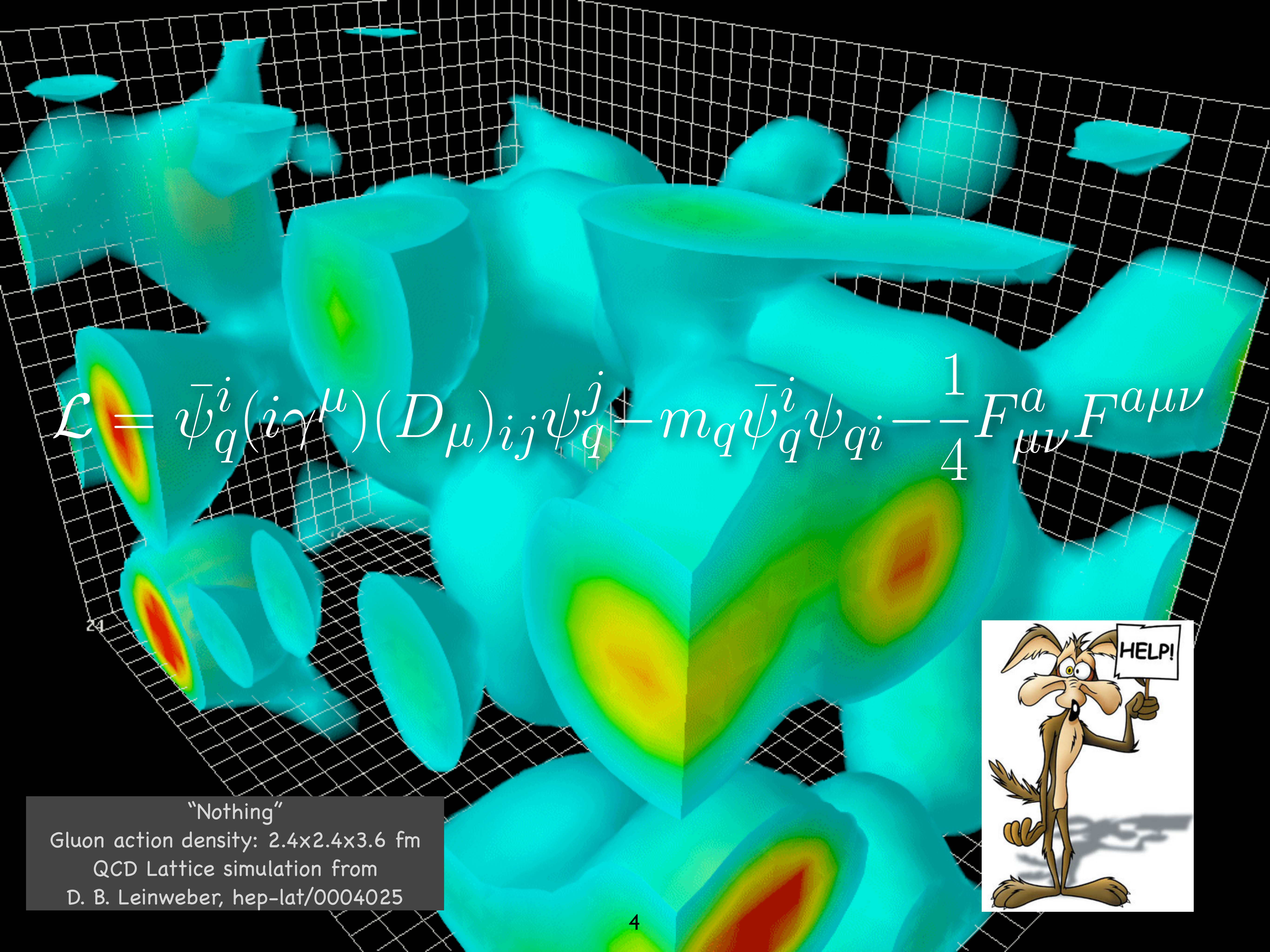
"Nothing"
Gluon action density: 2.4x2.4x3.6 fm
QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025



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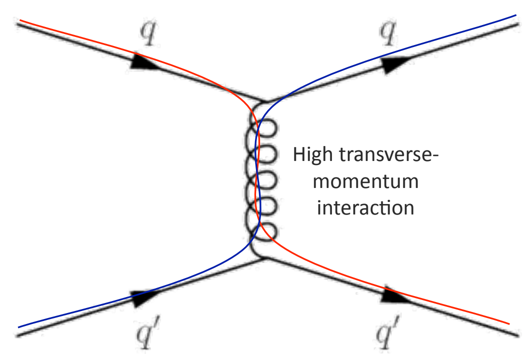
Perturbation Theory



Perturbation Theory

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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  - At least need well-understood PDFs
  - High precision = higher orders → enter QCD (and more QED)
- Isolation → indirect sensitivity to QCD
- Fakes → 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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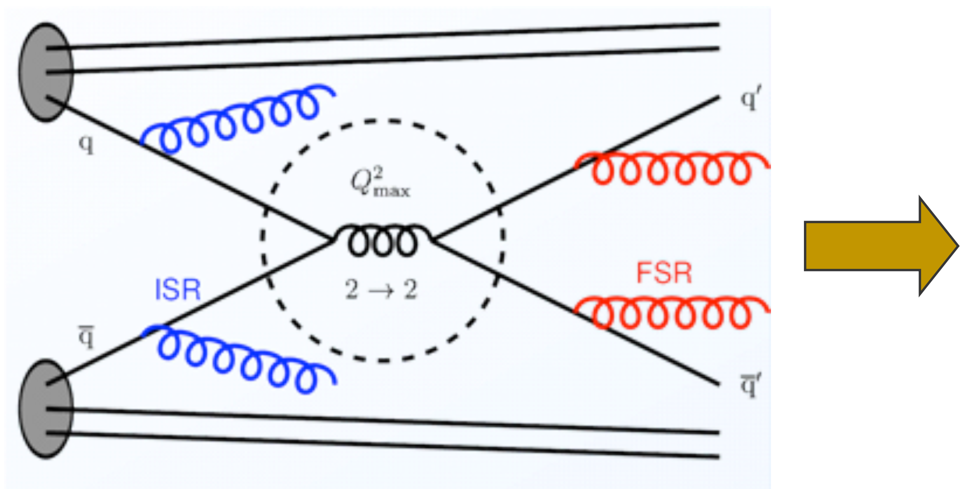
Monte Carlo Generators



Calculate Everything ≈ solve QCD → requires compromise!

Improve Born-level perturbation theory, by including the 'most significant' corrections
→ complete events → any observable you want

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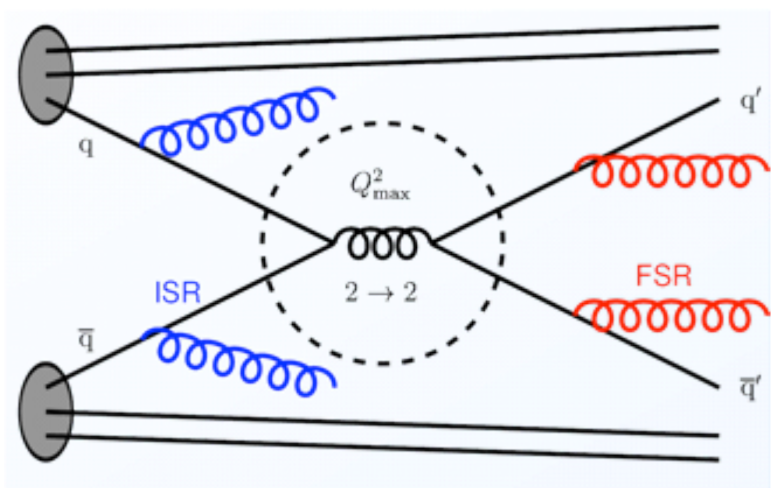

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Improve Born-level perturbation theory, by including the 'most significant' corrections
→ complete events → any observable you want

1. *Parton Showers*
2. *Matching*
3. *Hadronisation*
4. *The Underlying Event*

roughly ⟷

1. *Soft/Collinear Logarithms*
2. *Finite Terms, "K"-factors*
3. *Power Corrections (more if not IR safe)*
4. *?*

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, …)

Main Workhorses

HERWIG, PYTHIA and SHERPA intend to offer a convenient framework for LHC physics studies, but with slightly different emphasis:

PYTHIA (successor to JETSET, begun in 1978):
- originated in hadronization studies: the Lund string
- leading in development of multiple parton interactions
- pragmatic attitude to showers & matching
- the first multipurpose generator: machines & processes

HERWIG (successor to EARWIG, begun in 1984):
- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- large process library with spin correlations in decays

SHERPA (APACIC++/AMEGIC++, begun in 2000):
- own matrix-element calculator/generator
- extensive machinery for CKKW matching to showers
- PYTHIA-like MPI model + HERWIG-like hadronization model

Slide from T. Sjöstrand

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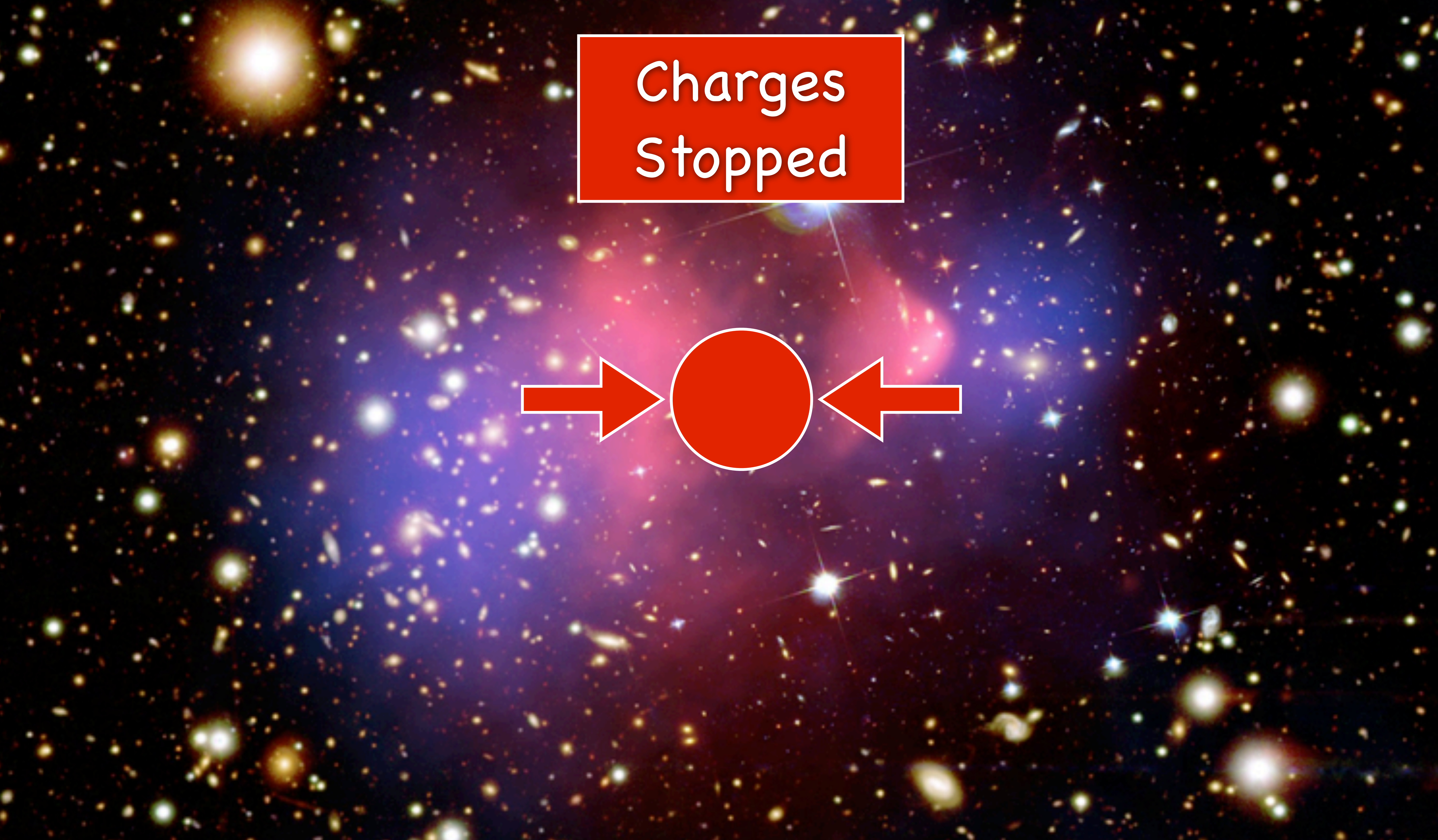
+ ALPGEN & MADGRAPH for matching,
+ MADGRAPH & CompHEP/CalcHEP for more BSM

+ Emerging serious tool: WHIZARD (OMEGA)

Slide from T. Sjöstrand

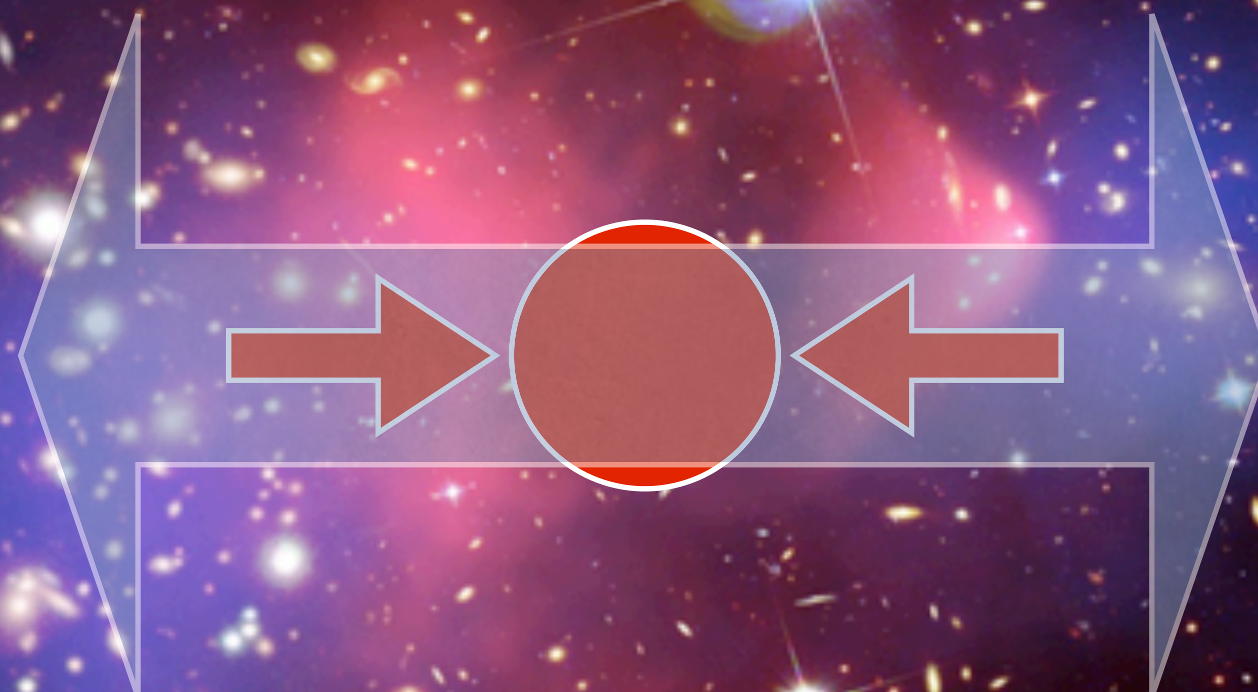
Bremsstrahlung

Bremsstrahlung



Bremsstrahlung

Charges Stopped



Associated field (fluctuations) continues

Bremsstrahlung

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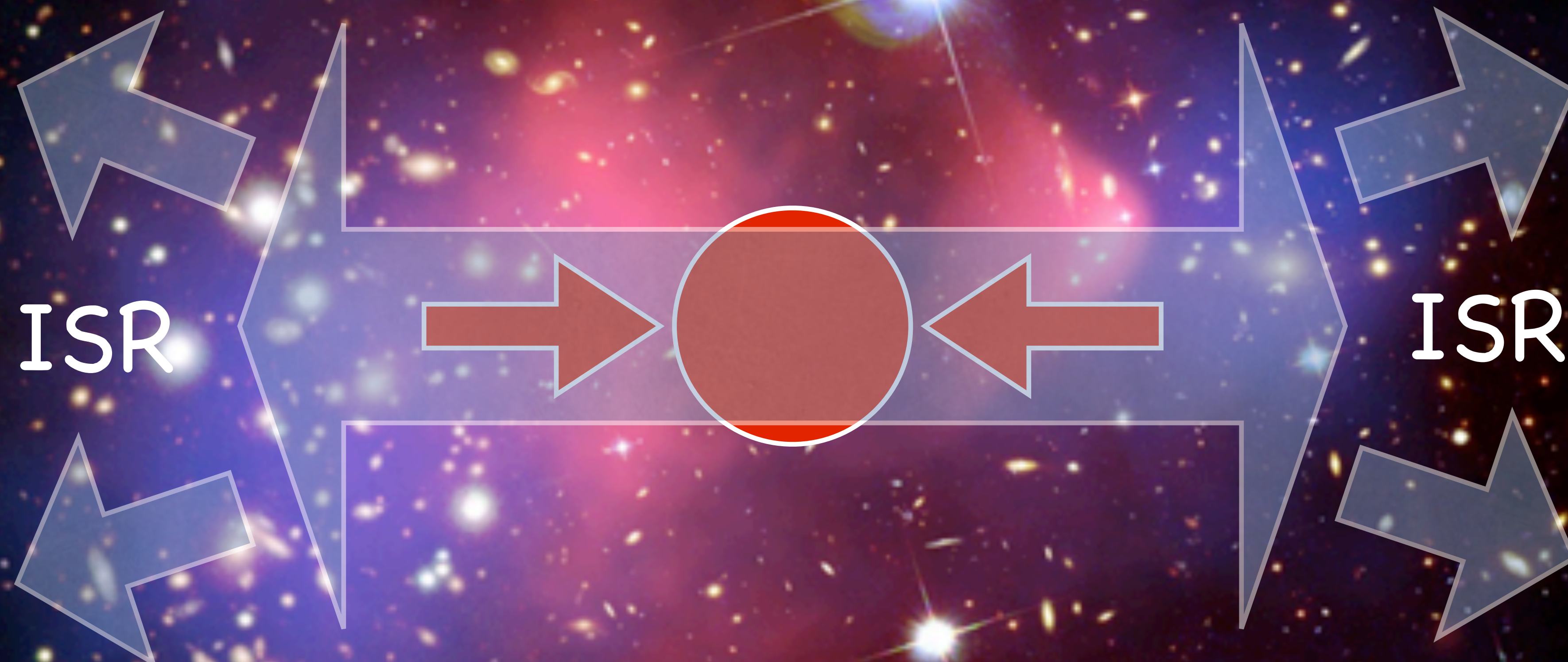

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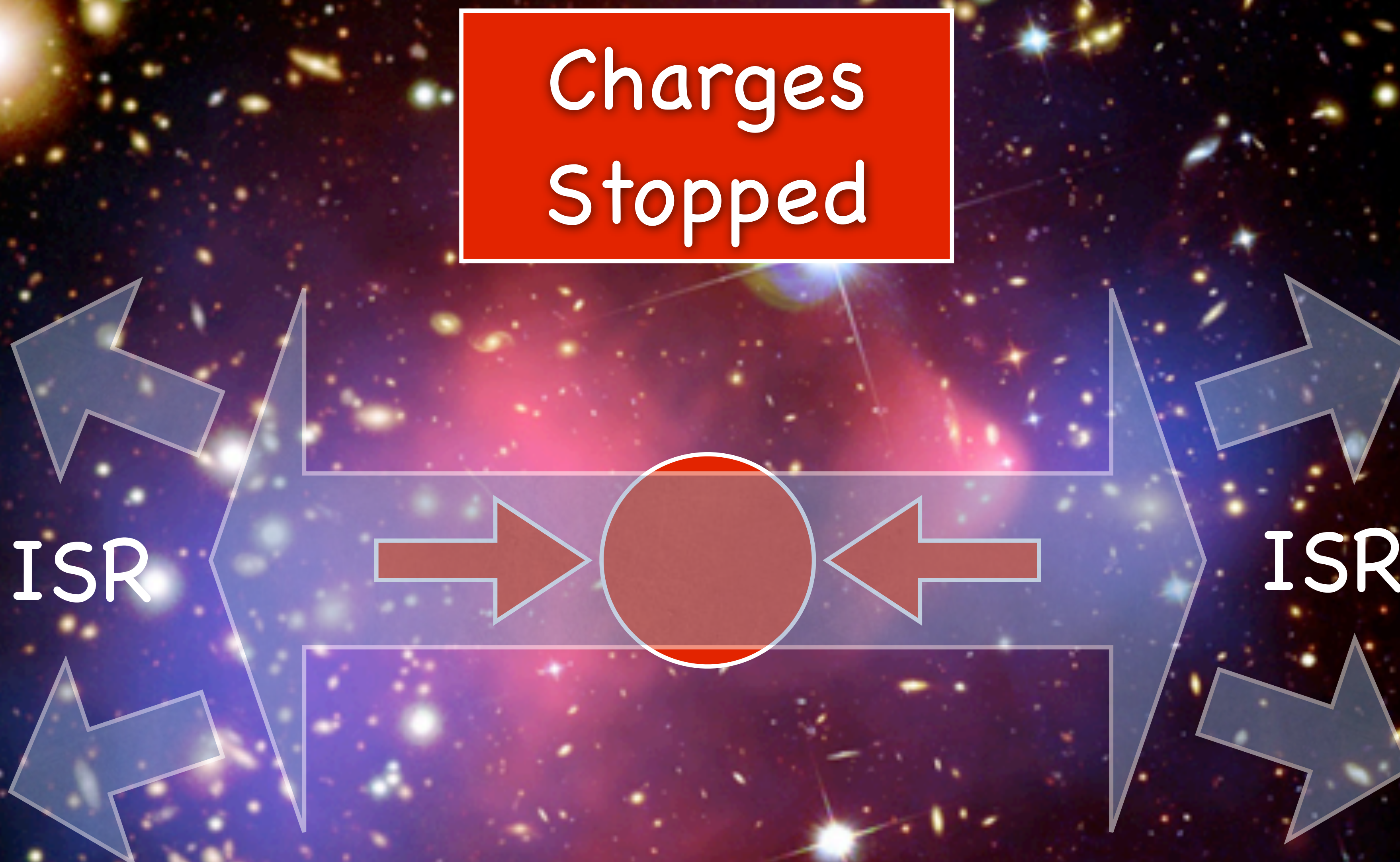
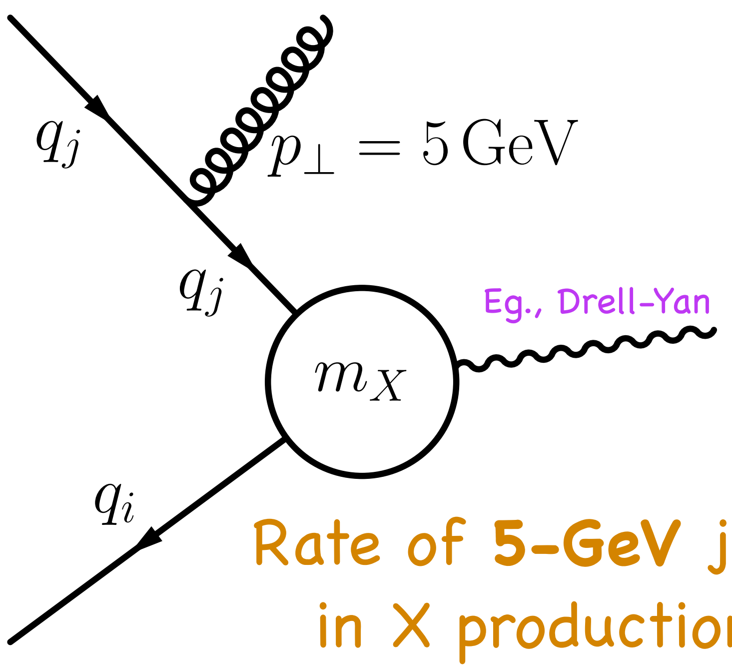


The harder they stop, the harder the fluctations that continue to become strahlung

Bremsstrahlung

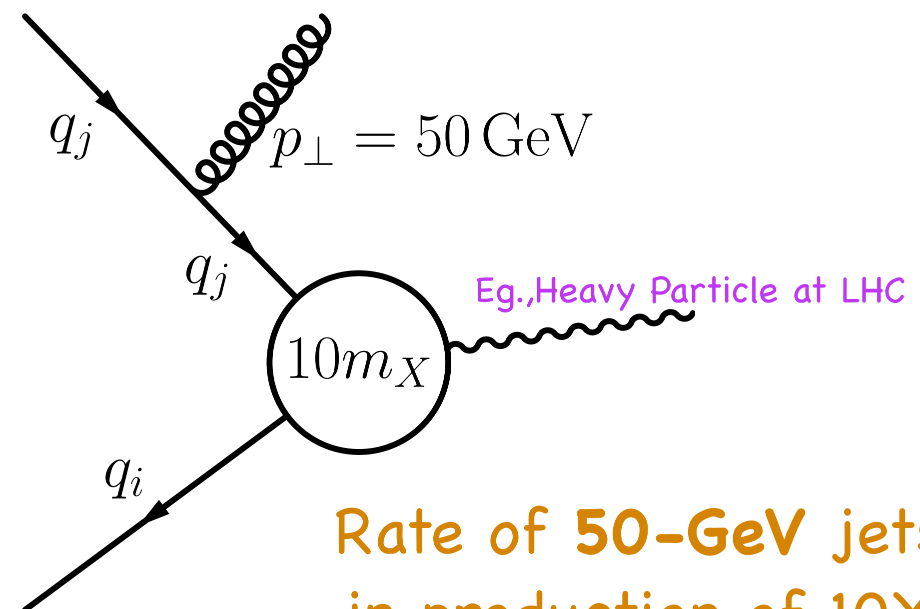
<u>Conformal QCD</u> (a.k.a. Bjorken scaling)

Rate of bremsstrahlung jets mainly depends on the **RATIO** of the jet p_T to the "hard scale"



Rate of **5-GeV** jets
in X production

$\approx$



Rate of **50-GeV** jets
in production of 10X

Soft/Collinear enhancements DIVERGENT for $p_T \ll m_X$

See, e.g.,
Plehn, Rainwater, PS: PLB645(2007)217
Plehn, Tait: 0810.2919 [hep-ph]
Alwall, de Visscher, Maltoni: JHEP 0902(2009)017

Computing Bremsstrahlung

1. Fixed-order QCD

Perturbation theory must be valid

→ α_s must be small

→ All $Q_i \gg \Lambda_{QCD}$

Single-scale: abensence of enhancements from soft/collinear singular (conformal) dynamics

→ All $Q_i/Q_j \approx 1$

→ All resolved scales $\gg \Lambda_{QCD}$ **AND** no large hierarchies

Fixed-Order QCD

All resolved scales >> Λ_{QCD} AND no large hierarchies

Trivially untrue for QCD

We're colliding, and observing, hadrons → small scales

We want to consider high-scale processes → large scale differences

→ A Priori, no perturbatively calculable observables in hadron-hadron collisions

Resummed QCD

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→ Initial-State Showers in MC

→ Final-State Showers (+ hadronization) in MC

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$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = \sum_{a,b} \sum_{f} \int_{\hat{X}_f} f_a(x_a, Q_i^2) f_b(x_b, Q_i^2) \frac{\mathrm{d}\hat{\sigma}_{ab\to f}(x_a, x_b, f, Q_i^2, Q_f^2)}{\mathrm{d}\hat{X}_f} D(\hat{X}_f \to X, Q_i^2, Q_f^2)$$

PDFs: needed to compute inclusive cross sections

→ Initial-State Showers in MC

FFs: needed to compute (semi-)exclusive cross sections

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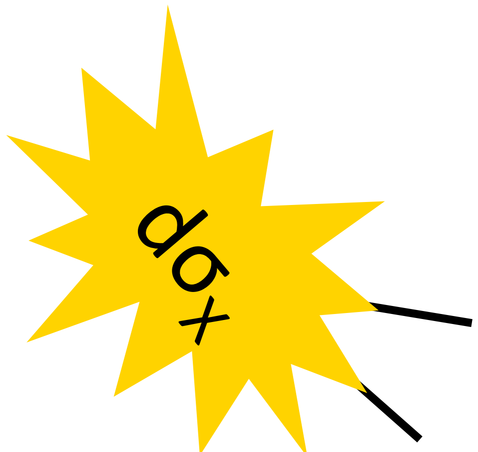
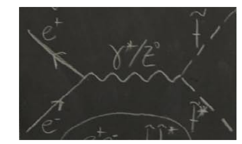
All resolved scales >> Λ_{QCD} AND X Infrared Safe

Bremsstrahlung



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

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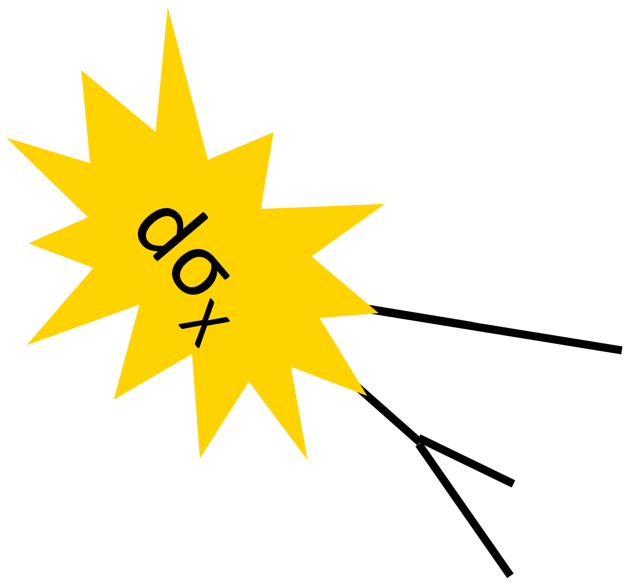
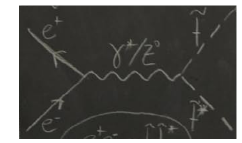


$$\mathrm{d}\sigma_X = \ldots$$ 

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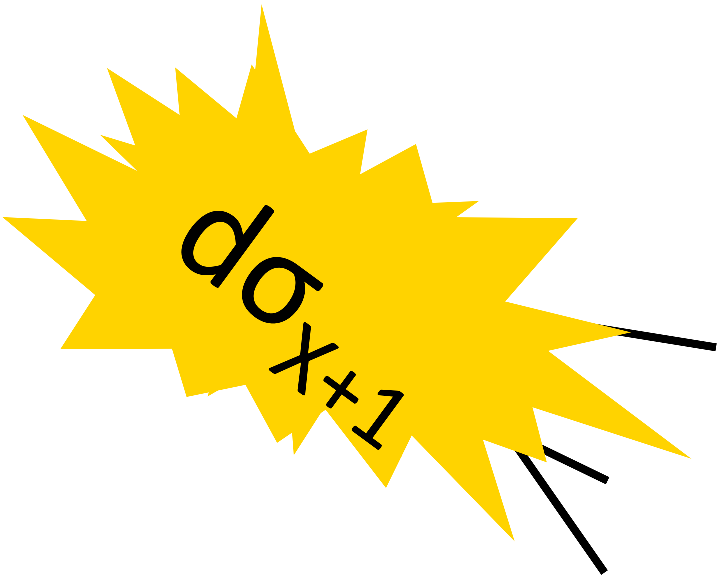

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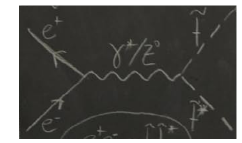

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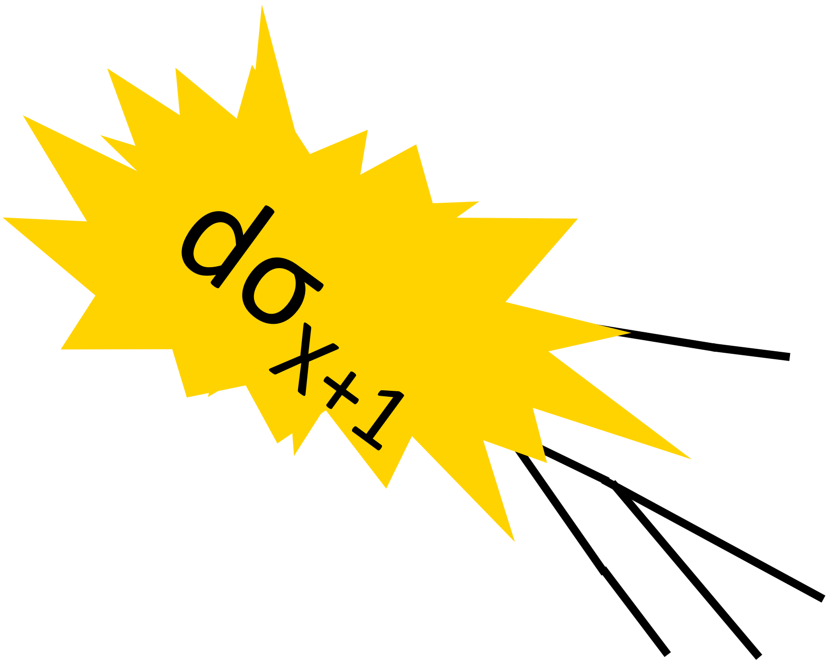
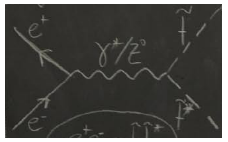


$$d\sigma_X = \ldots$$ 

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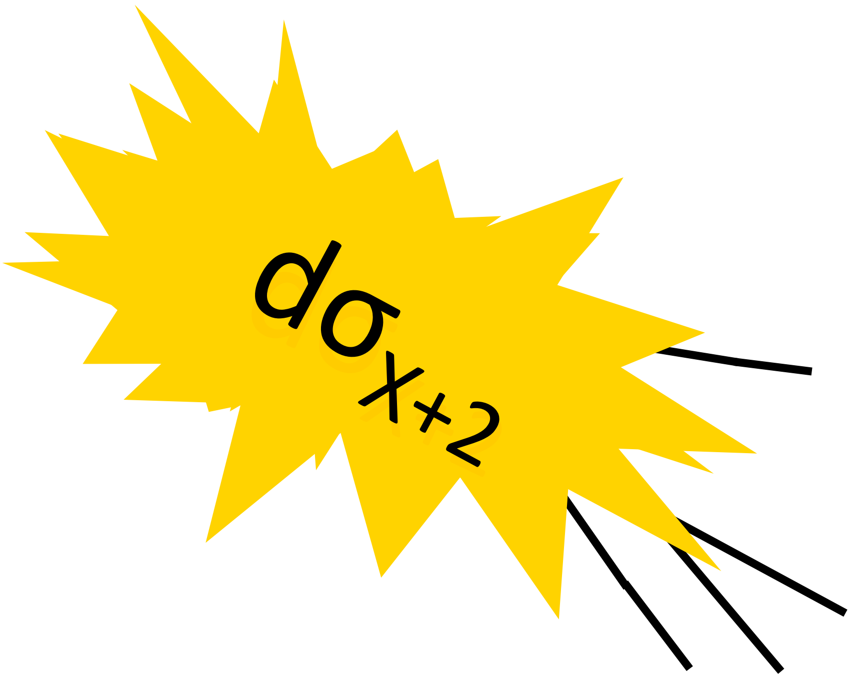
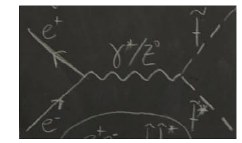


$$d\sigma_X = \ldots$$ 

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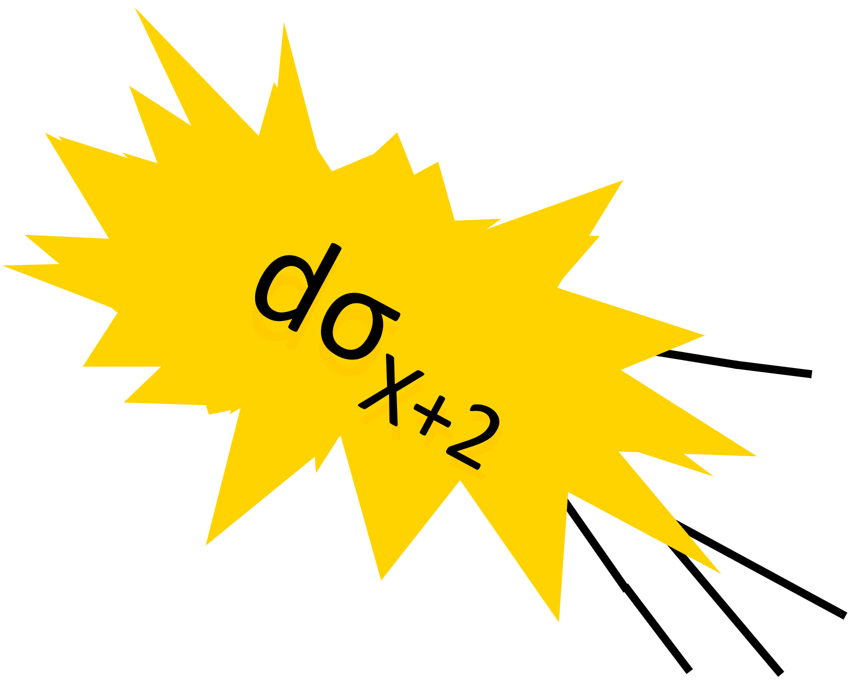
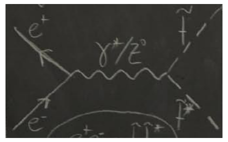


$$\mathrm{d}\sigma_X = \ldots$$ 

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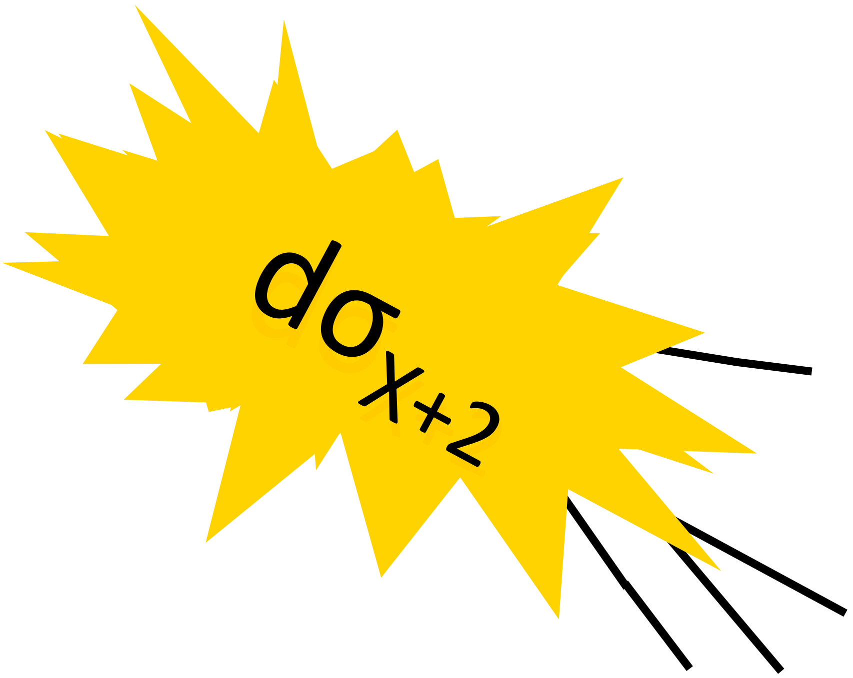
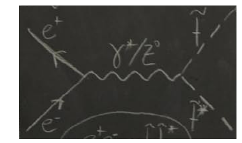


$$d\sigma_X = \dots$$ 

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This gives an approximation to infinite-order tree-level cross sections (here "DLA")

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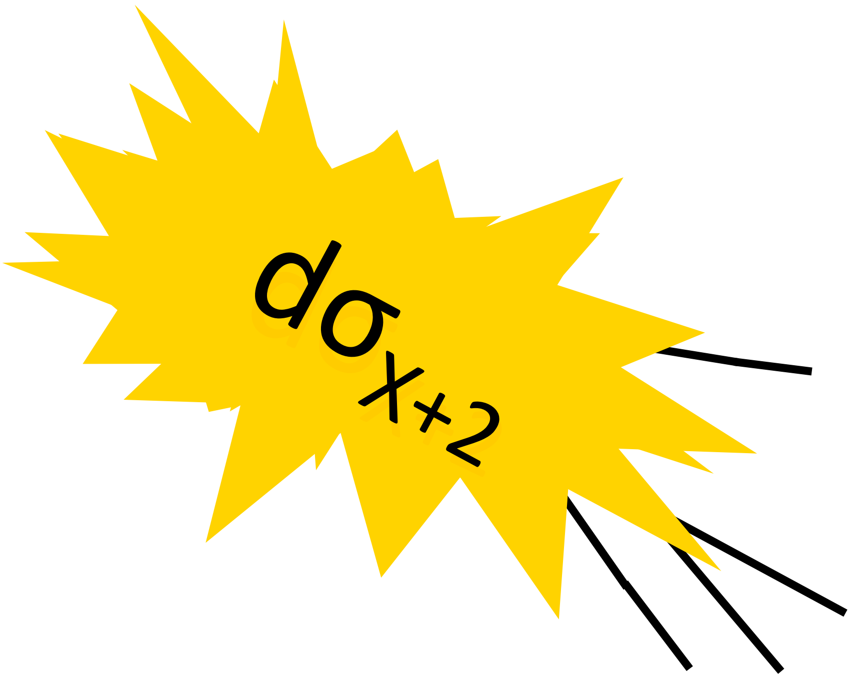
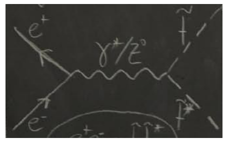


$$d\sigma_X = \ldots$$ 

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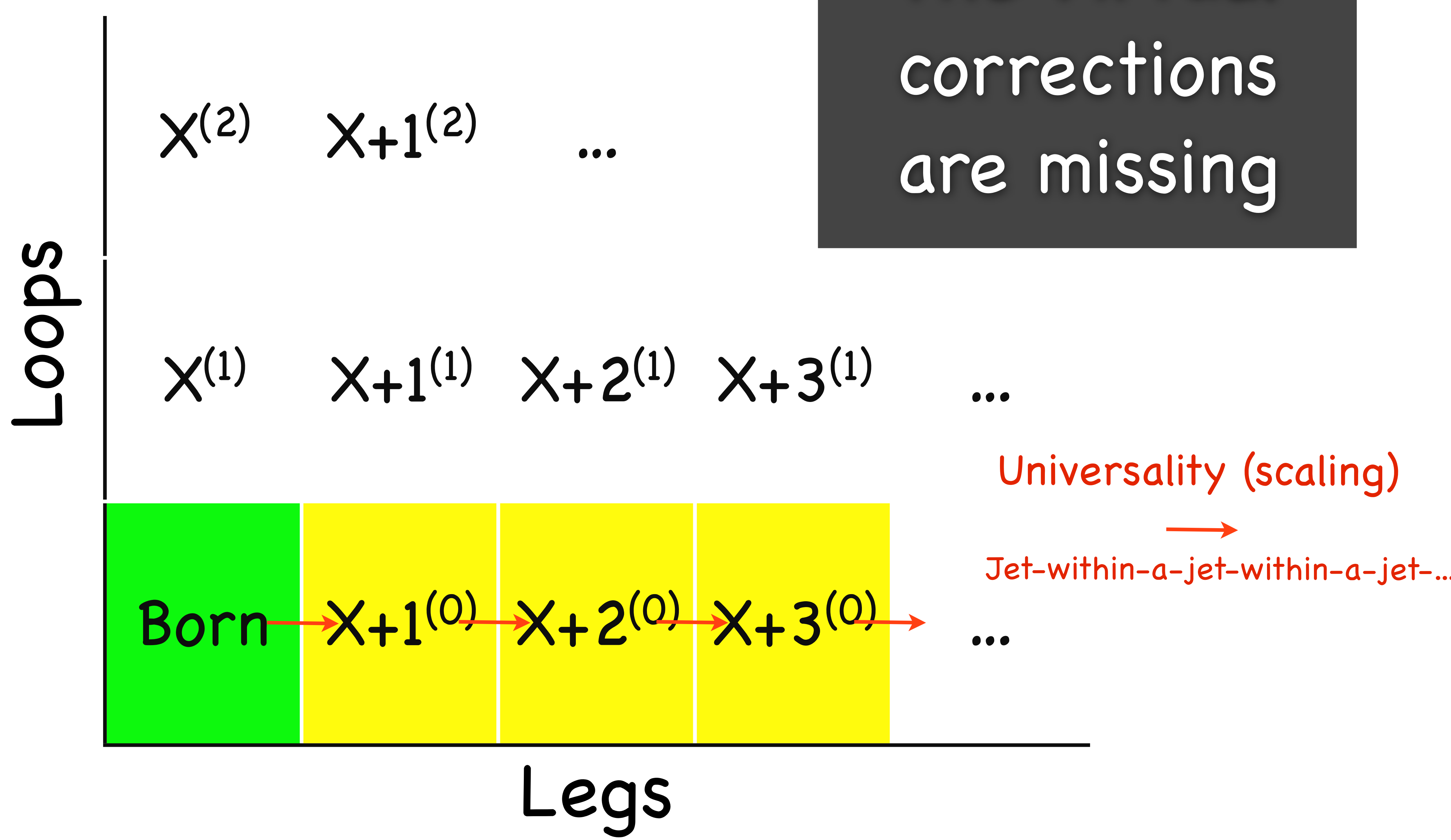
But something is not right …

Total cross section would be infinite …

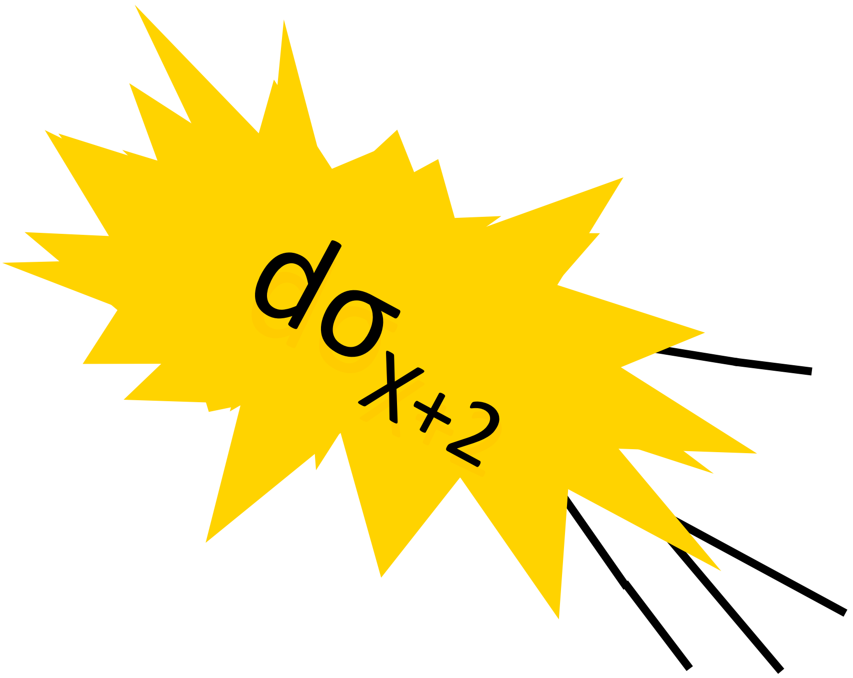
Loops and Legs

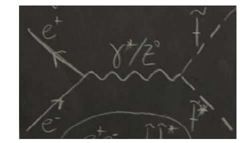
Summation

The Virtual corrections are missing



Resummation



$$d\sigma_X = \ldots$$ 

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Unitarity

KLN:

$$\text{Virt} = - \text{Int(Tree)} + \text{F}$$

In LL showers : neglect F

Imposed by Event *evolution*:

When (X) branches to (X+1):
Gain one (X+1). Loose one (X).

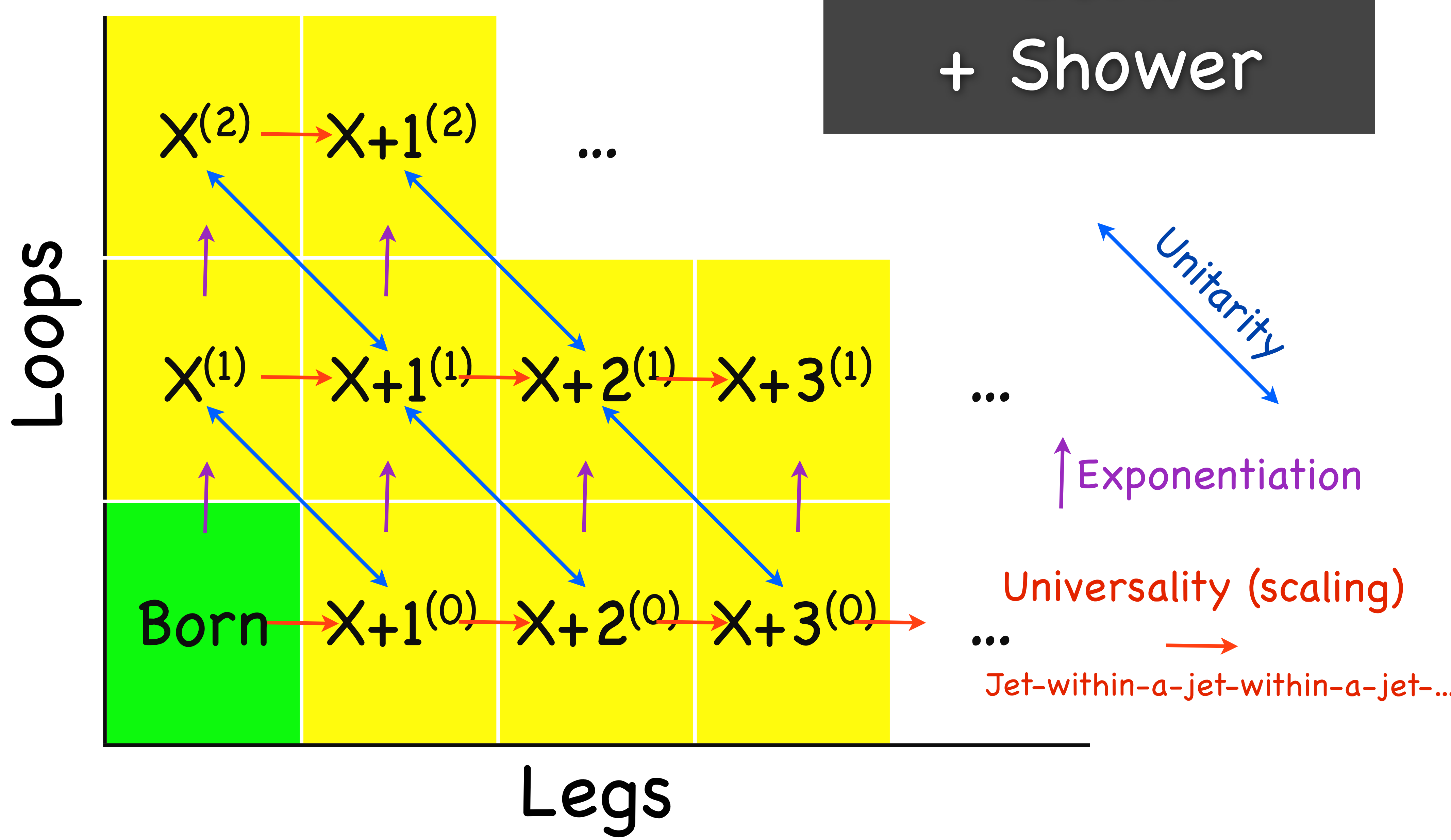
$\sigma_{X+1}(Q) = \sigma_{X;incl} - \sigma_{X;excl}(Q)$

→ includes both real and virtual corrections (in LL approx)

Bootstrapped pQCD

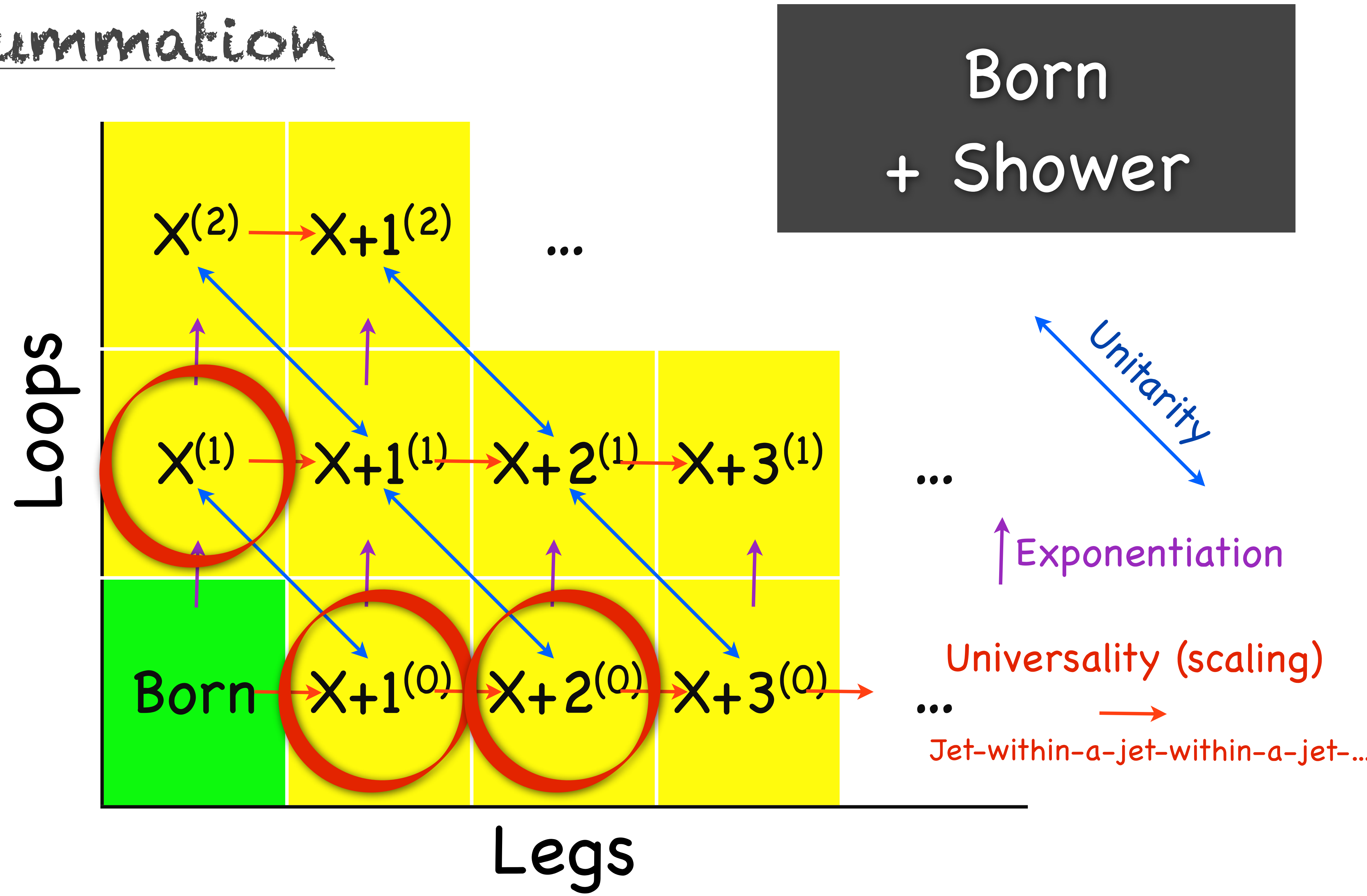
Resummation

Born + Shower



Bootstrapped pQCD

Resummation



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

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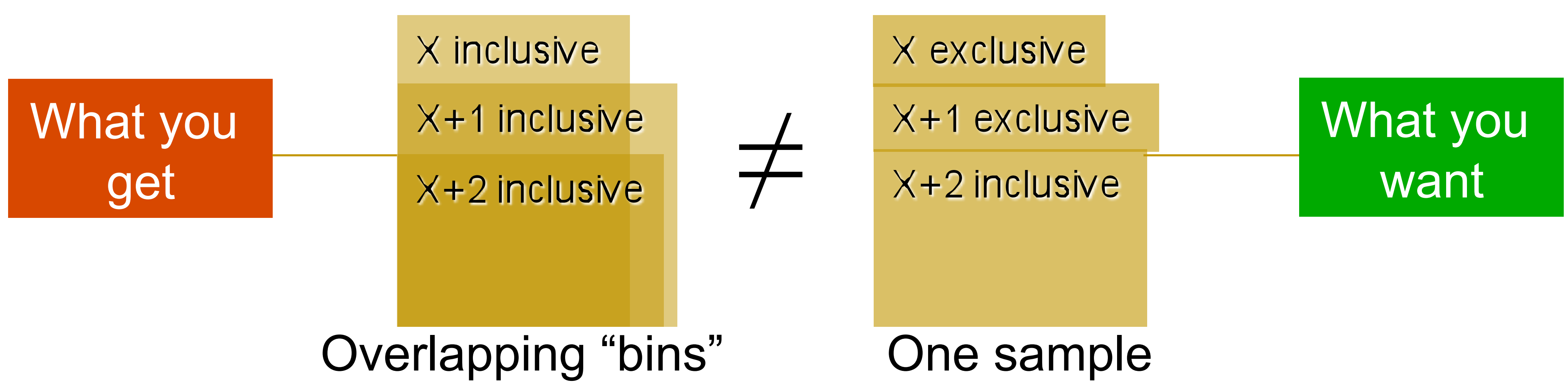
Run generator for … (+ shower)

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

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

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

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Solution 1: "Additive" (most widespread)

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

Add event samples, with modified weights

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

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

$w_{X+n} = |M_{X+n}|^2 - \text{Shower}\{w_X, w_{X+1}, \ldots, w_{X+n-1}\}$ + *Shower*

Only CKKW and MLM

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 & MLM : for all X+n @ LO (force Shower = 0 above "matching scale" and add ME there)
SHERPA (CKKW), ALPGEN (MLM + HW/PY), MADGRAPH (MLM + HW/PY), PYTHIA8 (CKKW-L from LHE files), …

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Solution 2: "Multiplicative"

One event sample

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

Make a "course correction" to the shower at each order

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

$R_{X+n} = |M_{X+n}|^2/Shower\{w_{X+n-1}\}$ + *Shower*   Only VINCIA

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) → POWHEG Box, HERWIG++, …

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

SPEED : milliseconds / Event

MS/EVENT		Matched through:			
Monte Carlo	Strategy	Z→3	Z→4	Z→5	Z→6
Pythia 8 *Initialization time ~ 0*	TS	0.22	Z→qq *(q=udscb)* + shower. Matched and unweighted. Hadronization off *gfortran/g++ with gcc v.4.4 -O2 on single 3.06 GHz processor with 4GB memory*		
Vincia *(sector, Q_{match} = 5 GeV)* *Initialization time ~ 0*	GKS	0.26	0.50	1.40	6.70
Sherpa *(Q_{match} = 5 GeV)*	CKKW (expect similar scaling for MLM)	5.15*	53.00*	220.00*	400.00*
Initialization time =		1.5 minutes	7 minutes	22 minutes	2.2 hours

Generator Versions: Pythia 6.425 *(Perugia 2011 tune)*, Pythia 8.150, Sherpa 1.3.0, Vincia 1.026 *(without uncertainty bands, NLL/NLC=OFF)*

Efficient Matching with Sector Showers
J. Lopez-Villarejo & PS : JHEP 1111 (2011) 150

Additional Sources of Particle Production

$Q_F >> \Lambda_{QCD}$

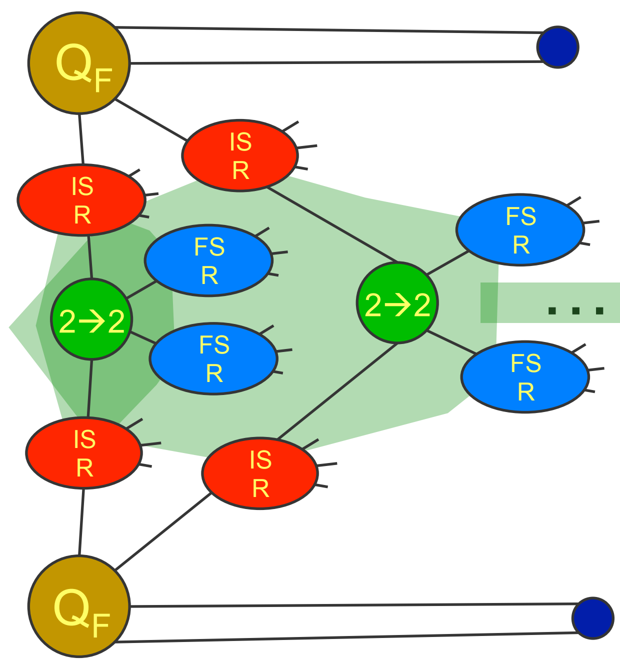
ME+ISR/FSR

+ perturbative MPI

+

Stuff at

$Q_F \sim \Lambda_{QCD}$



Multiple (perturbative) parton-parton Interactions occurring in each single hadron-hadron collision

→ **underlying event**

(distinct from pile-up caused by high lumi)

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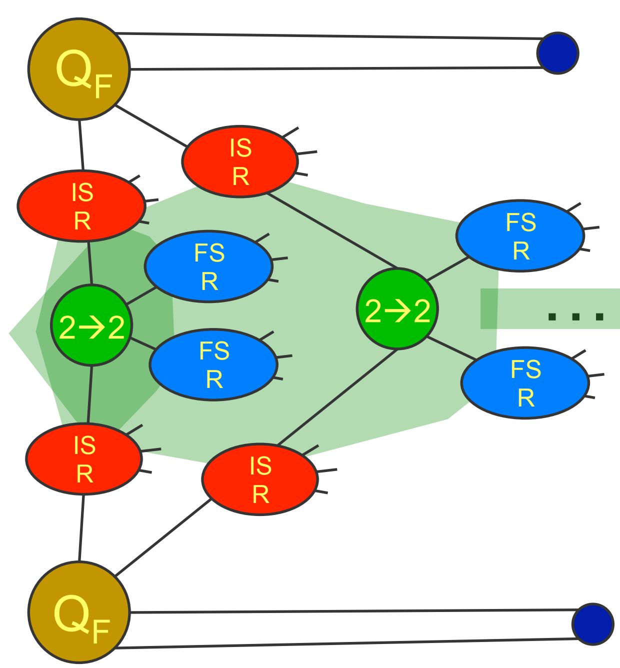

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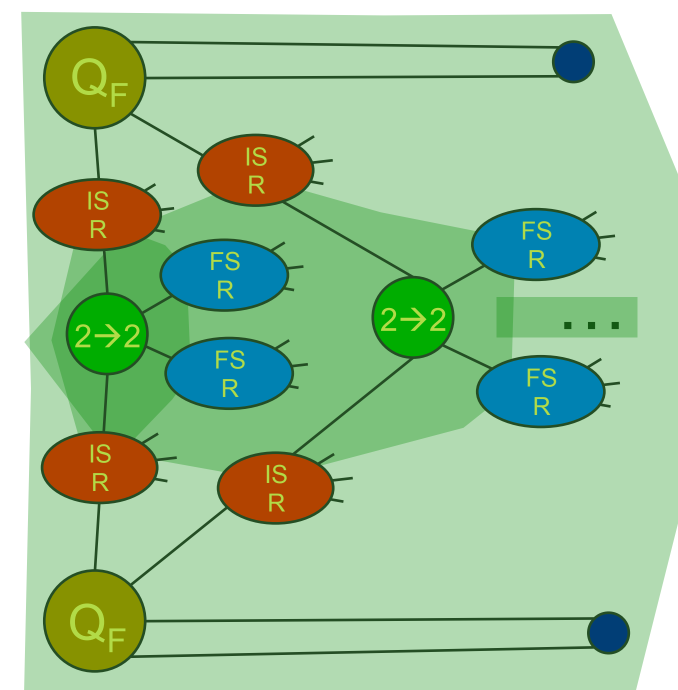

Need-to-know issues for IR sensitive quantities (e.g., N_{ch})

Hadronization

Hadronization

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_{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)*
3. Sequential decays into **secondary hadrons** (e.g., rho > pi pi, Lambda > n pi0, pi0 > gamma gamma, ...)

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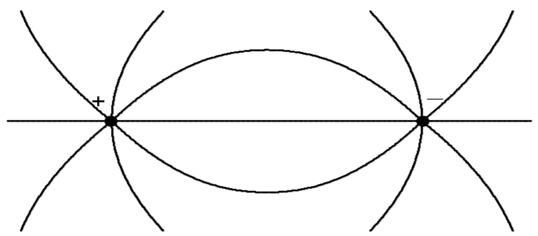
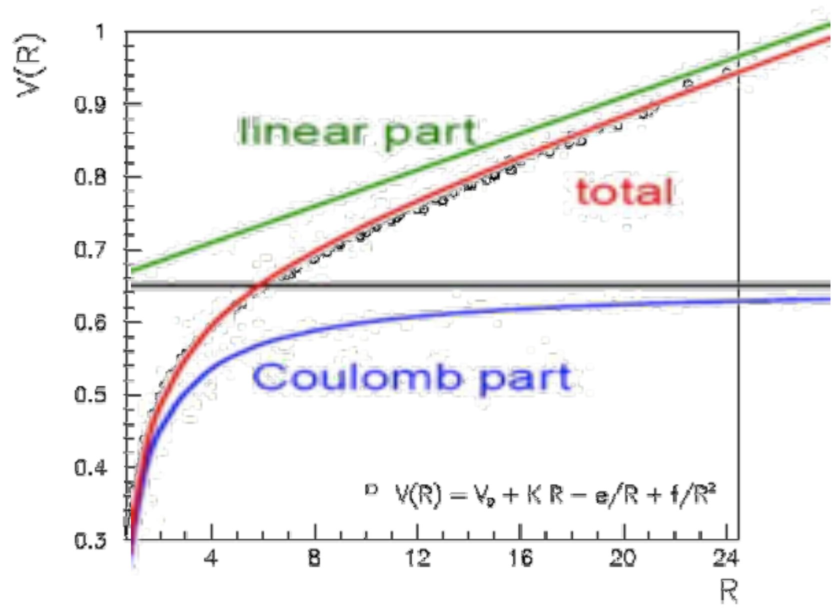
From Partons to Strings

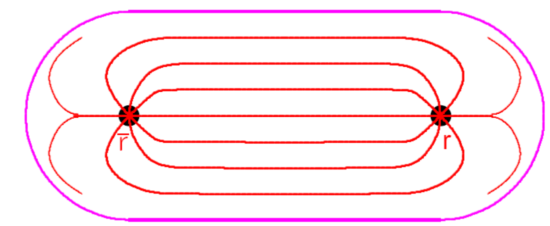
Short Distances ~ pQCD



Partons



Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

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

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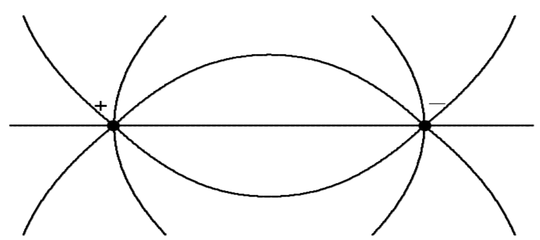

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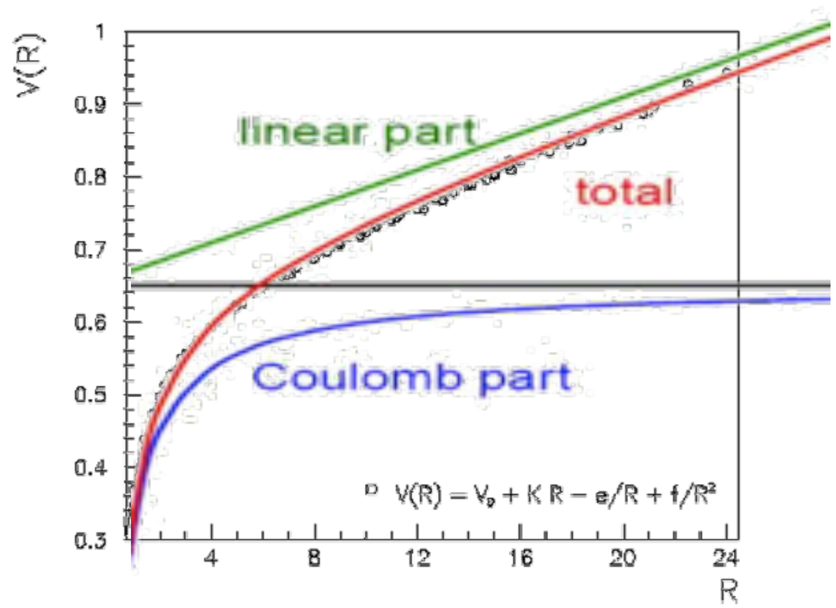

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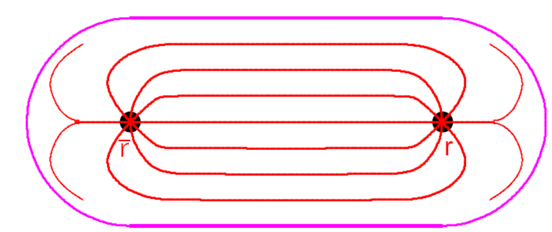

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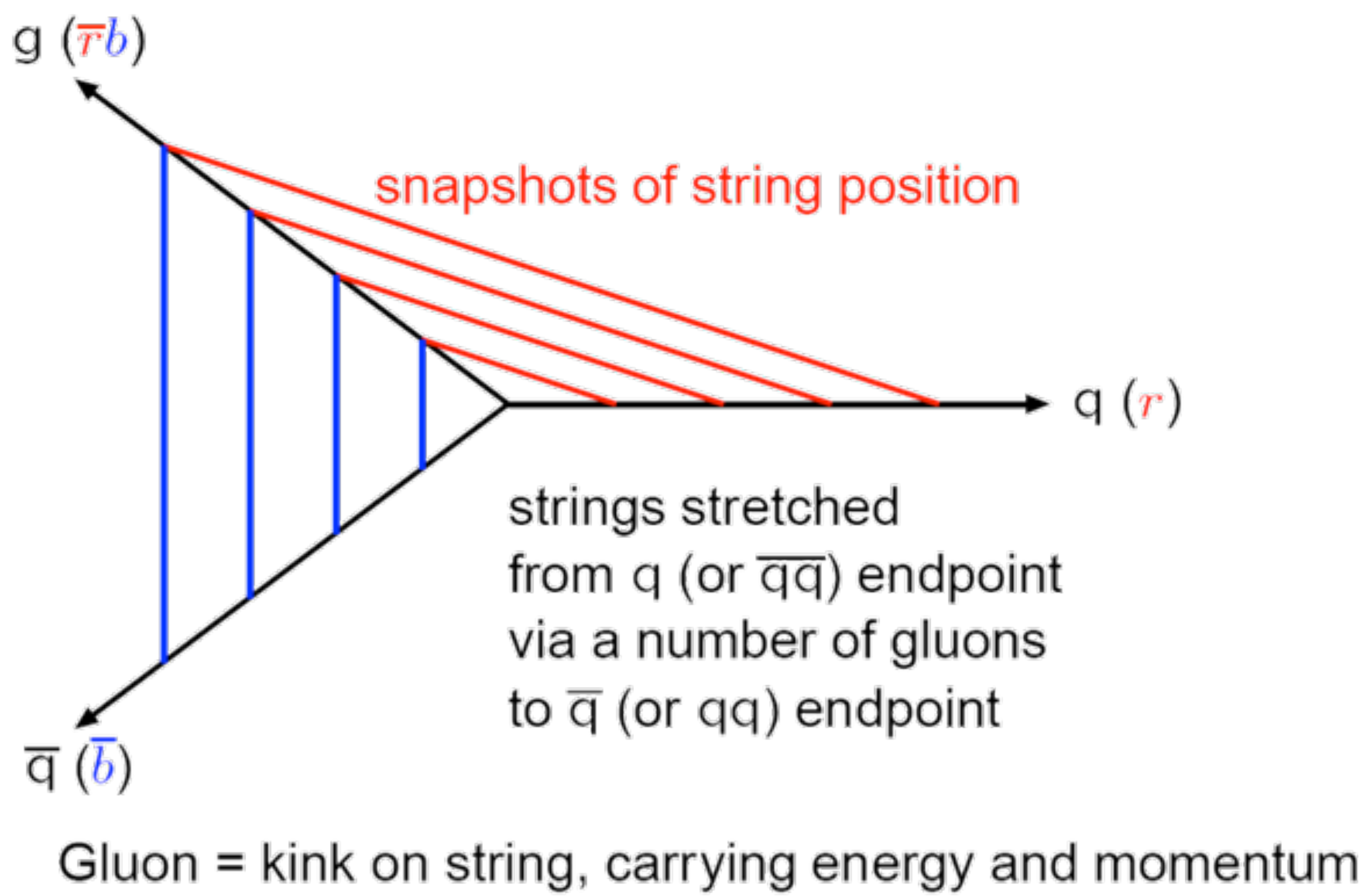
- **Motivates a model:**
  - Separation of transverse and longitudinal degrees of freedom
  - Simple description as 1+1 dimensional worldsheet – string – with Lorentz invariant formalism

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**



Simple space-time picture
Details of string breaks more complicated

Conclusions

- **QCD Phenomenology** is witnessing a rapid evolution: LO & NLO matching, better showers, tuning, interfaces ...
  - Driven by demand of high precision in complex LHC environment with huge phase space
- BSM Physics
  - Generally relies on chains of tools (MC4BSM)
  - Sufficient to reach O(10%) accuracy, with hard work, though must be careful with scale hierarchies, width effects, decay distributions, …
  - Next machine is a long way off → must strive to build capacity for yet higher precision, to get max from LHC data.
- Ultimate limit set by solutions to pQCD (getting better) and then the **really** hard stuff
  - Like Hadronization, Underlying Event, Diffraction, … (& BSM equivalents?)
  - For which fundamentally new ideas may be needed