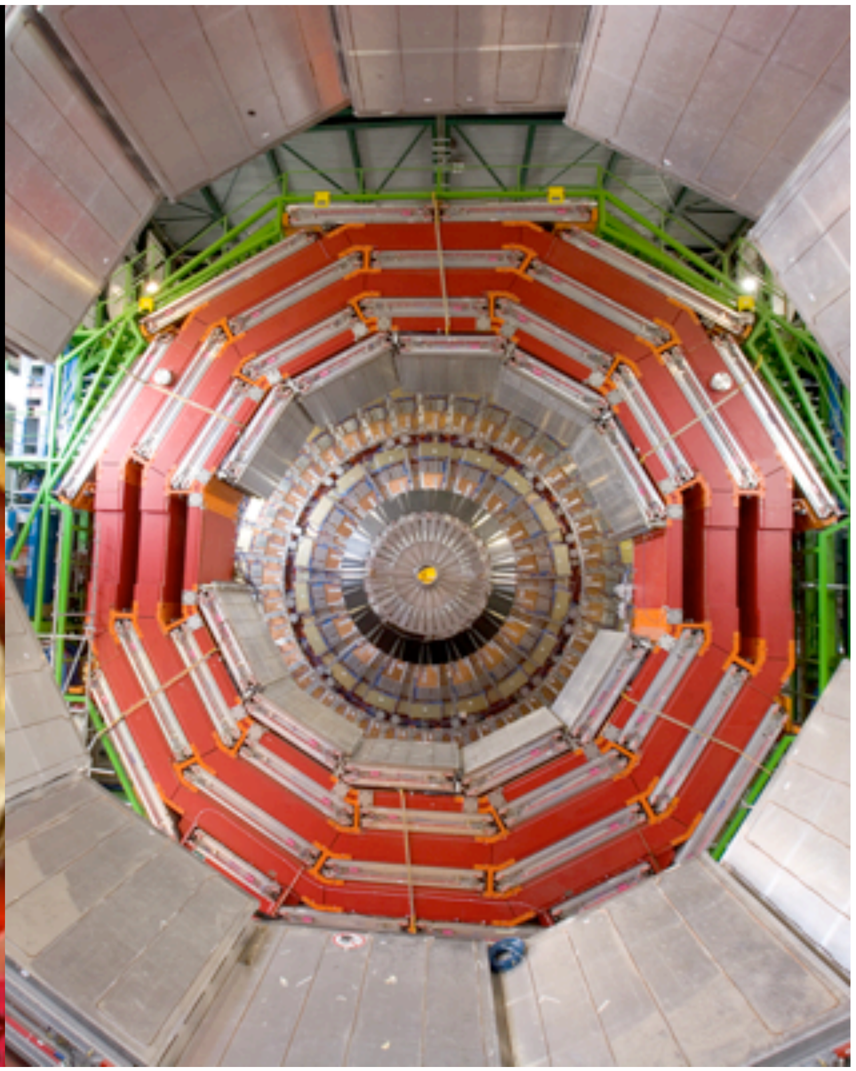
6th MC for BSM Workshop, Cornell, Ithaca, March 2012

MC Overview

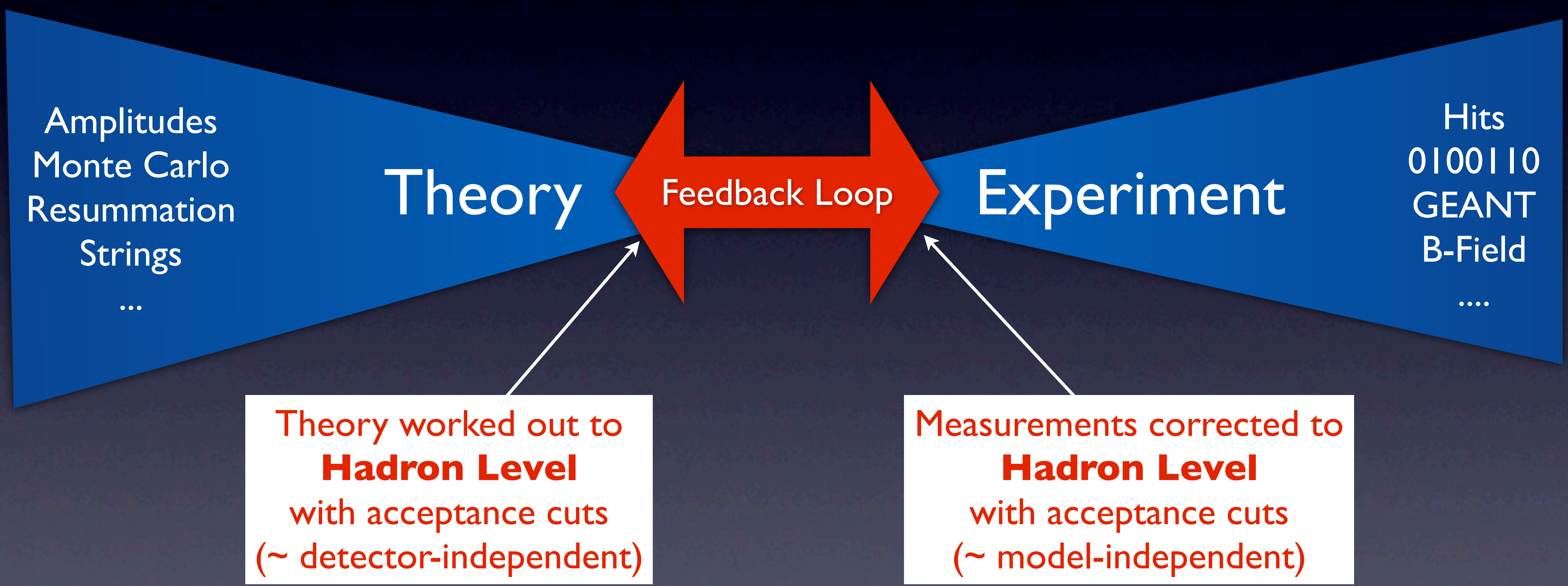



Peter Skands
(CERN-TH)

Count what is Countable

Measure what is Measurable

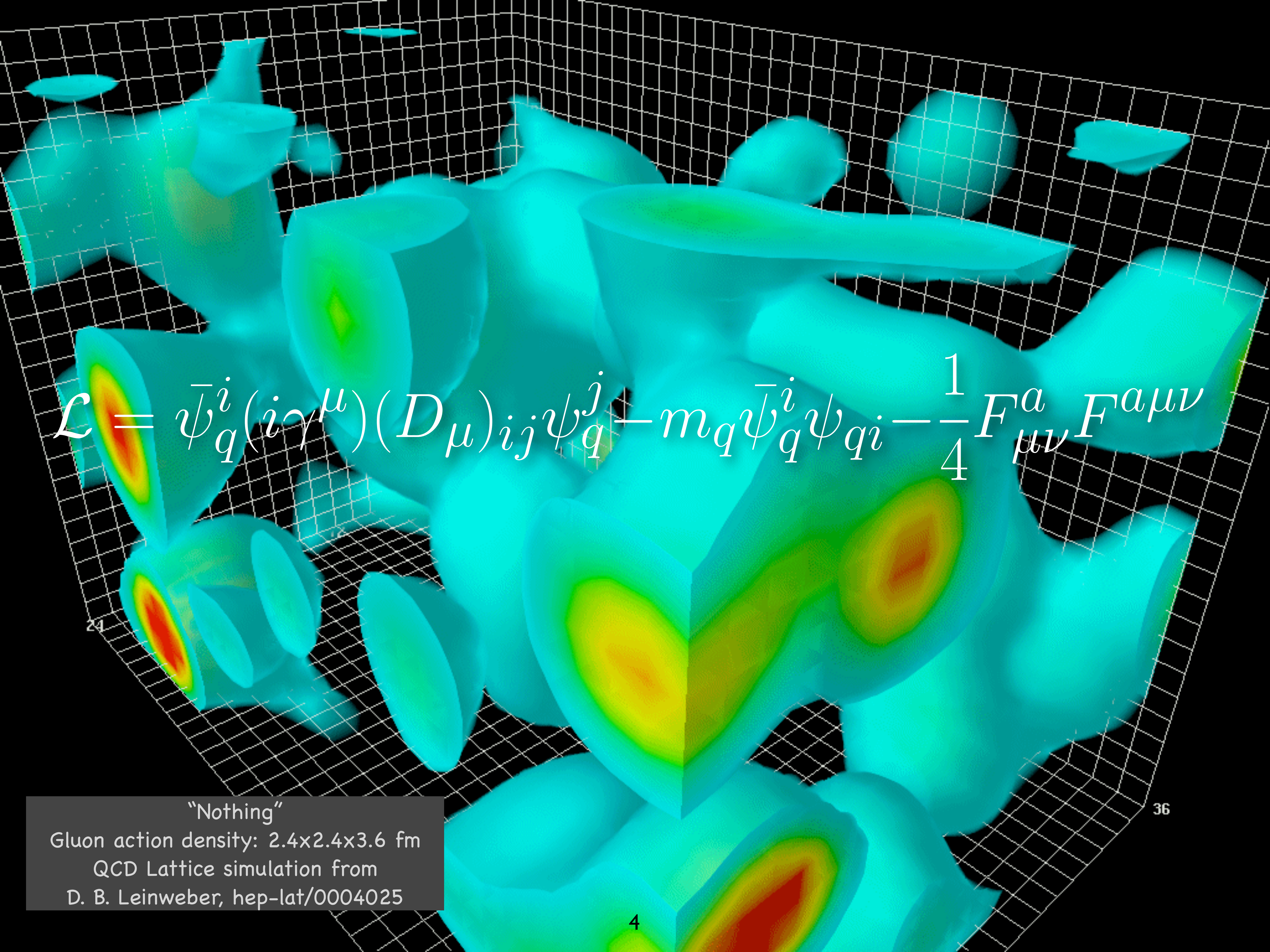
(and keep working up the beam)



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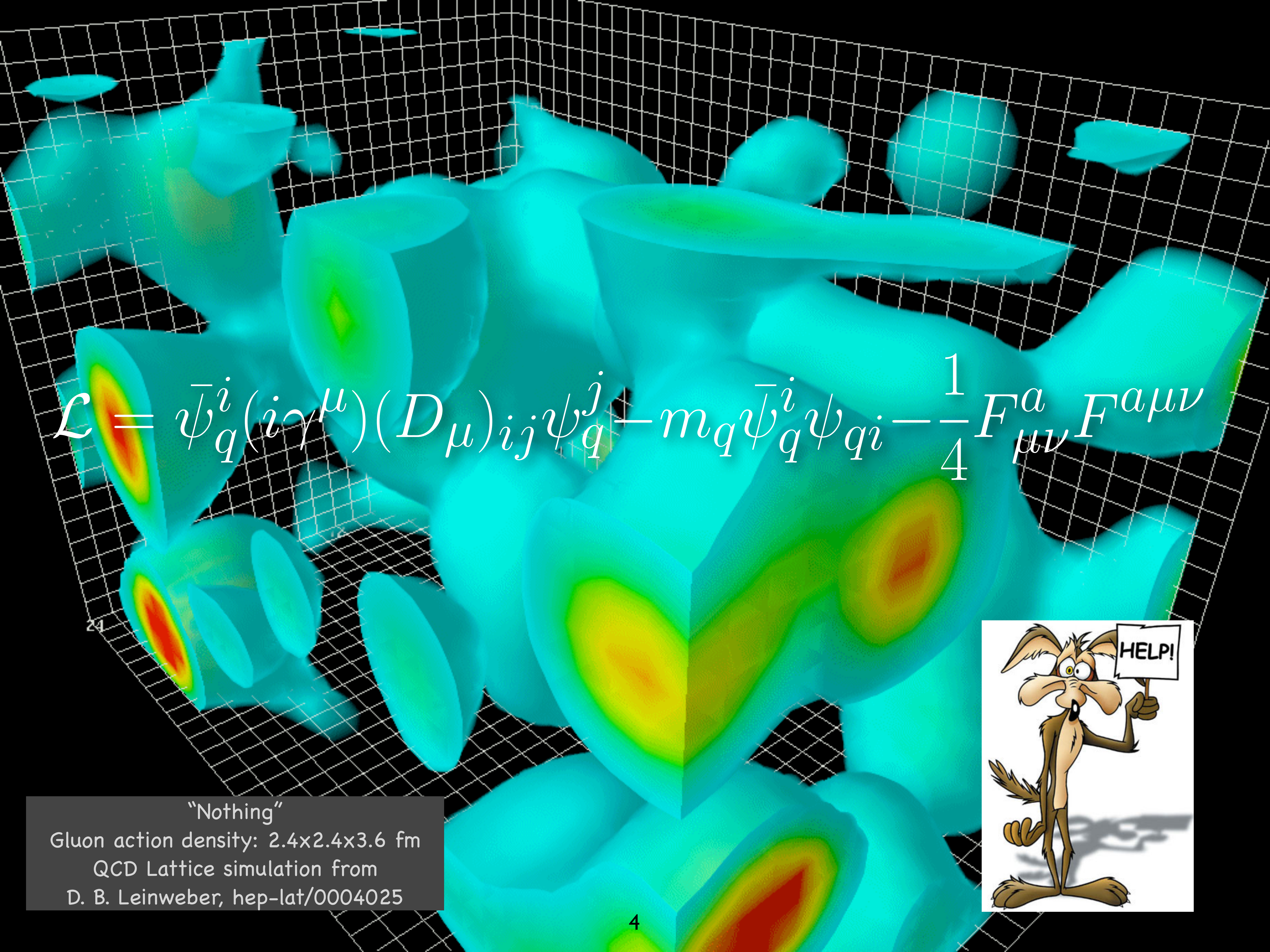
"Nothing"
Gluon action density: 2.4x2.4x3.6 fm
QCD Lattice simulation from
D. B. Leinweber, hep-lat/0004025



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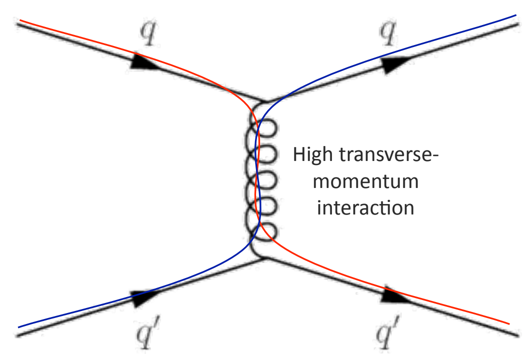
Perturbation Theory



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

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

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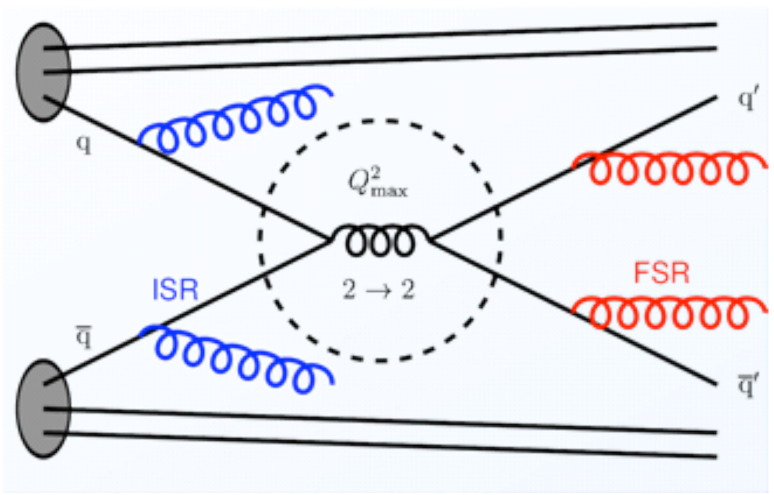
Monte Carlo Generators

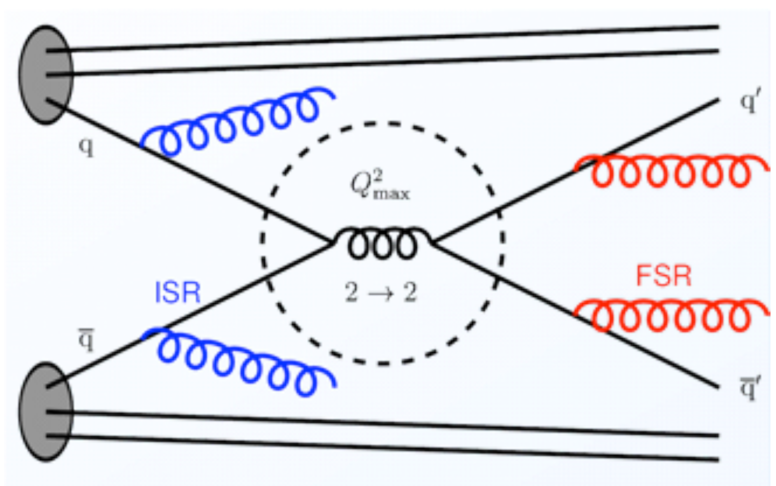


Calculate Everything ≈ solve QCD → requires compromise!

Improve Born-level perturbation theory, by including the 'most significant' corrections

→ complete events → any observable you want

Monte Carlo Generators



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1. Parton Showers		*1. Soft/Collinear Logarithms*
2. Matching	roughly	*2. Finite Terms, "K"-factors*
3. Hadronisation		*3. Power Corrections (more if not IR safe)*
4. The Underlying Event		*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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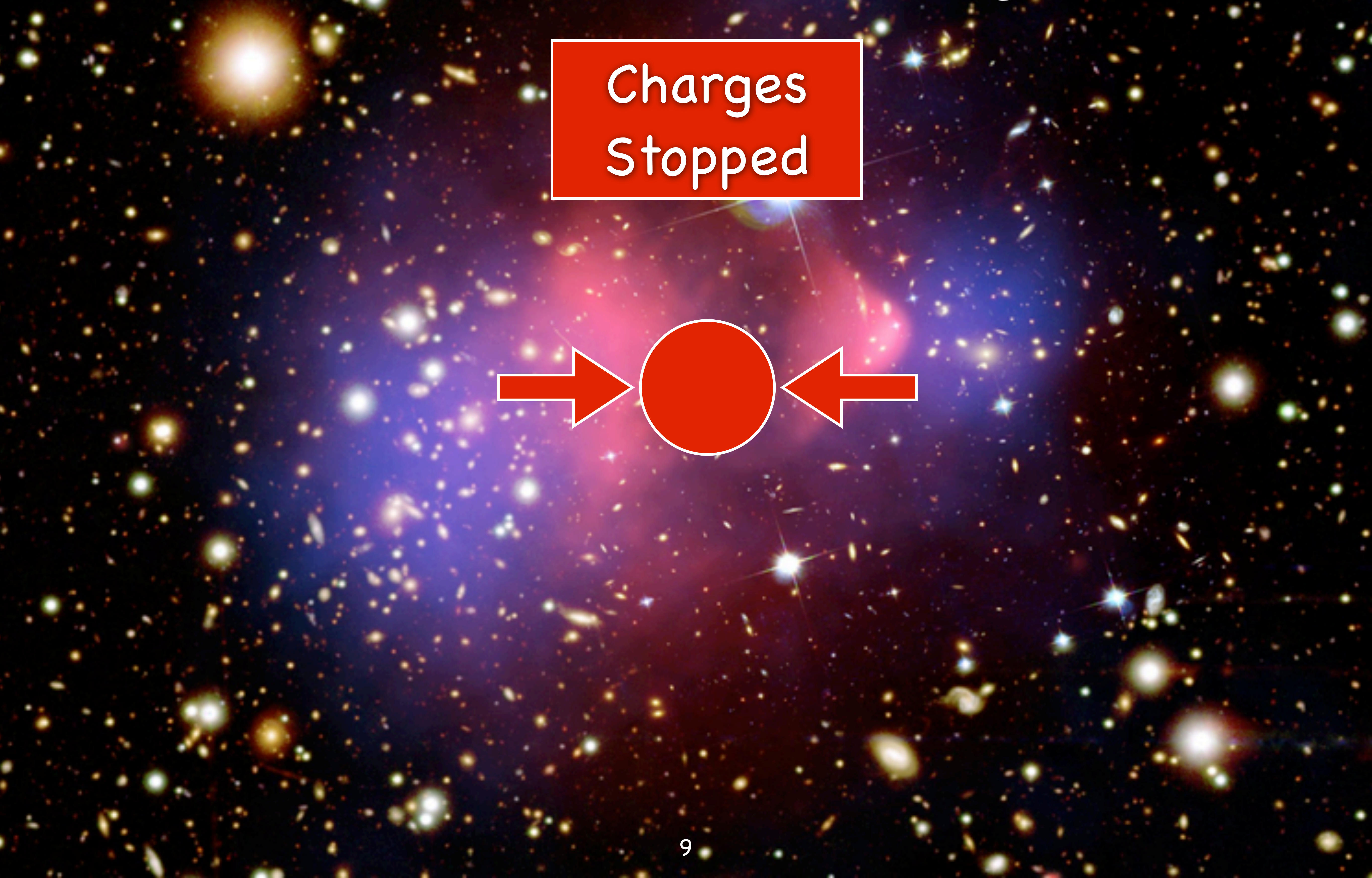
+ WHIZARD (OMEGA): emerging serious tool with focus on BSM

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

Slide from T. Sjöstrand

Bremsstrahlung

Bremsstrahlung



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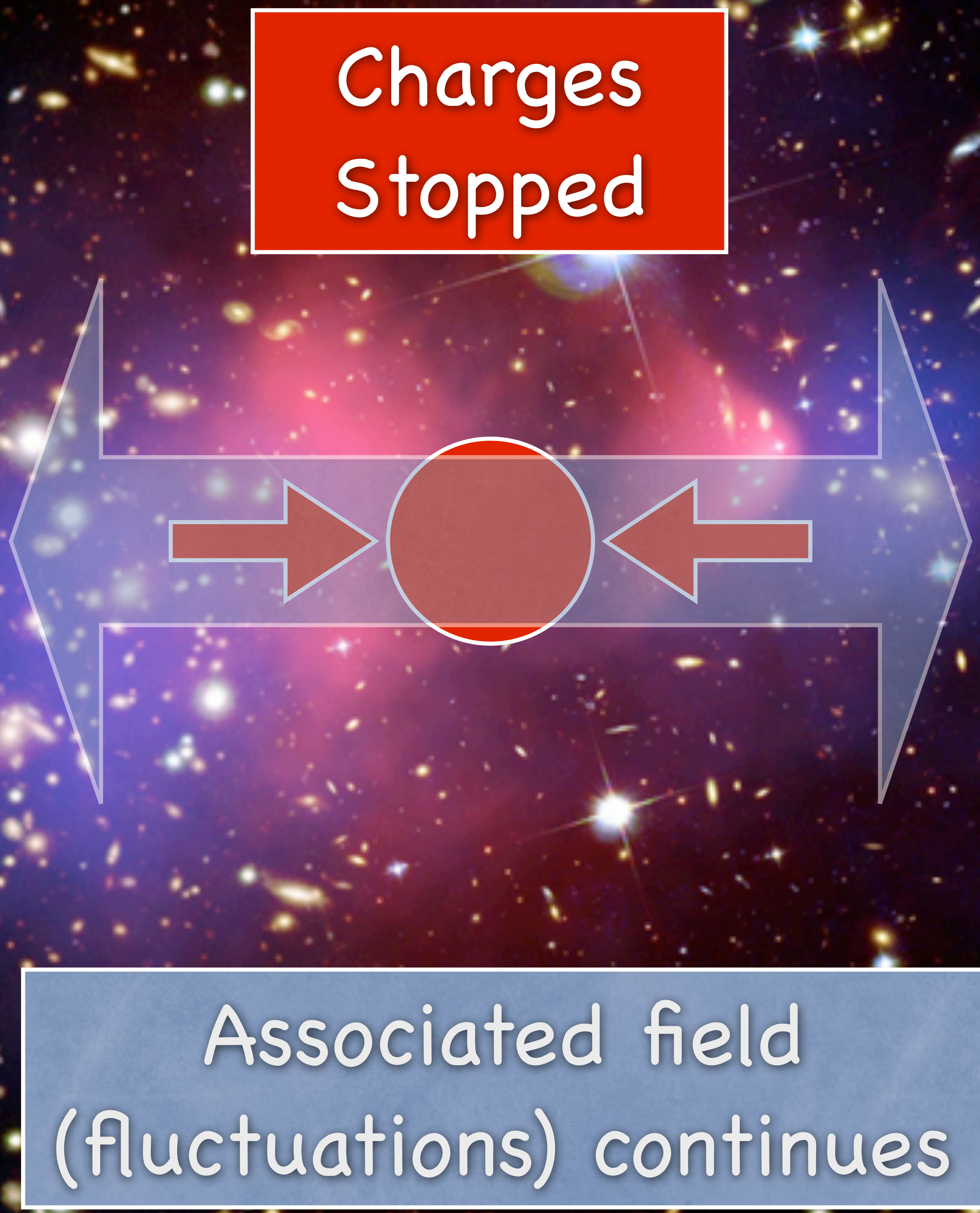
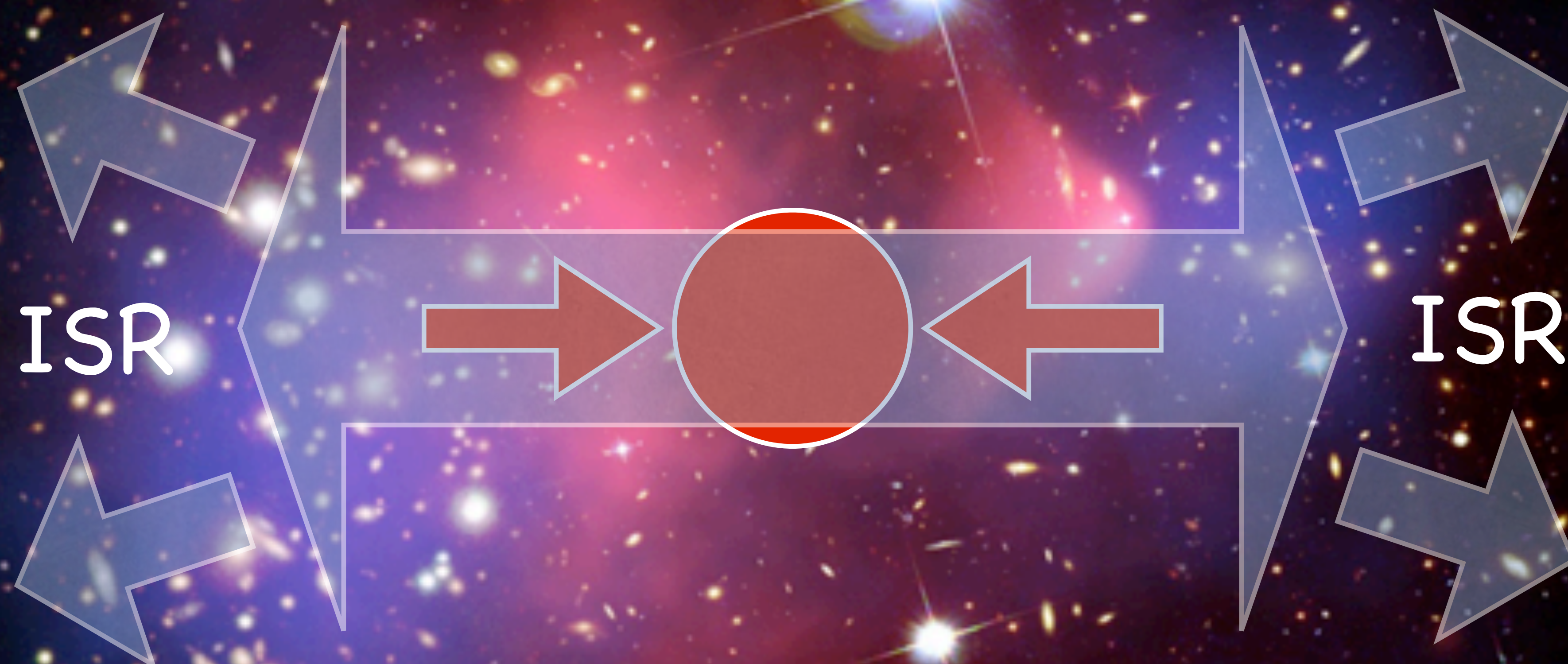


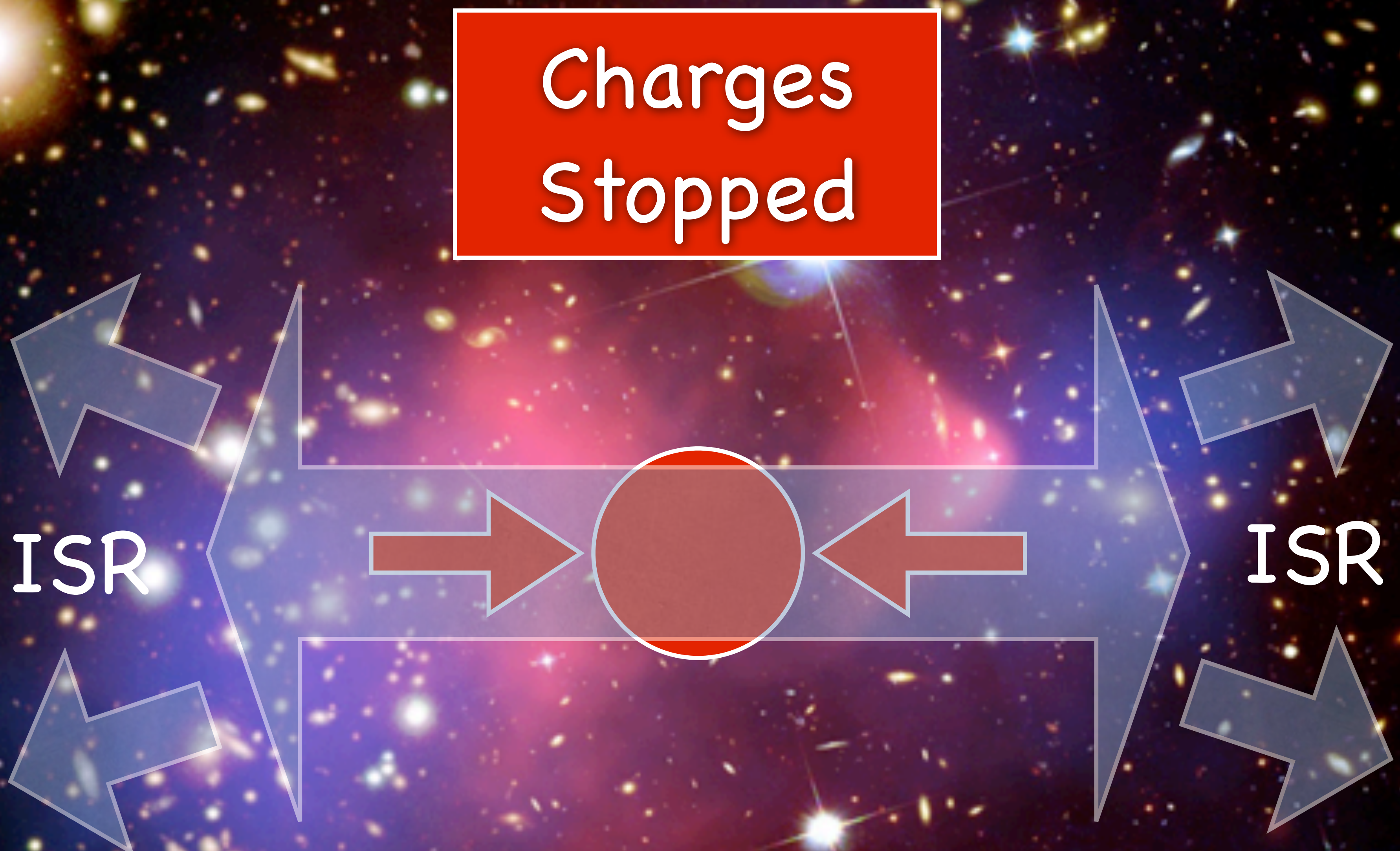
Bremsstrahlung

Charges Stopped



Associated field (fluctuations) continues

Bremsstrahlung

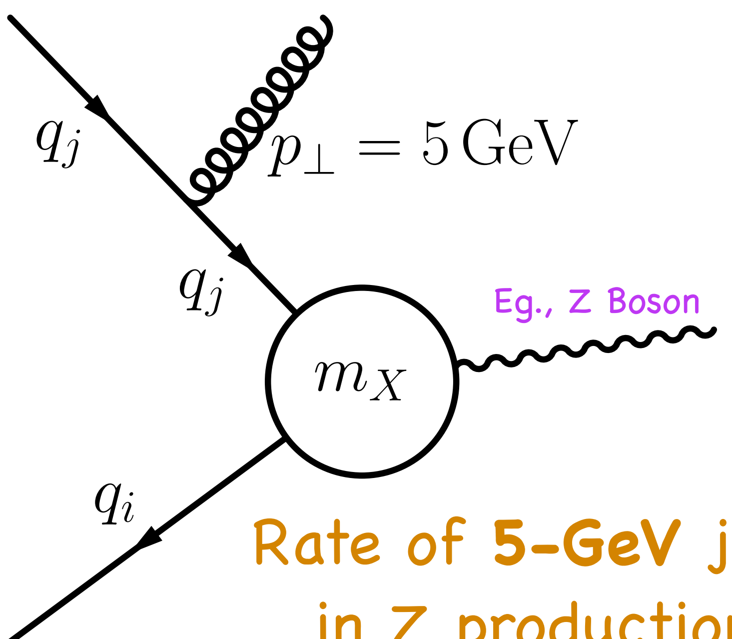


The harder they stop, the harder the fluctations that continue to become strahlung

Bremsstrahlung

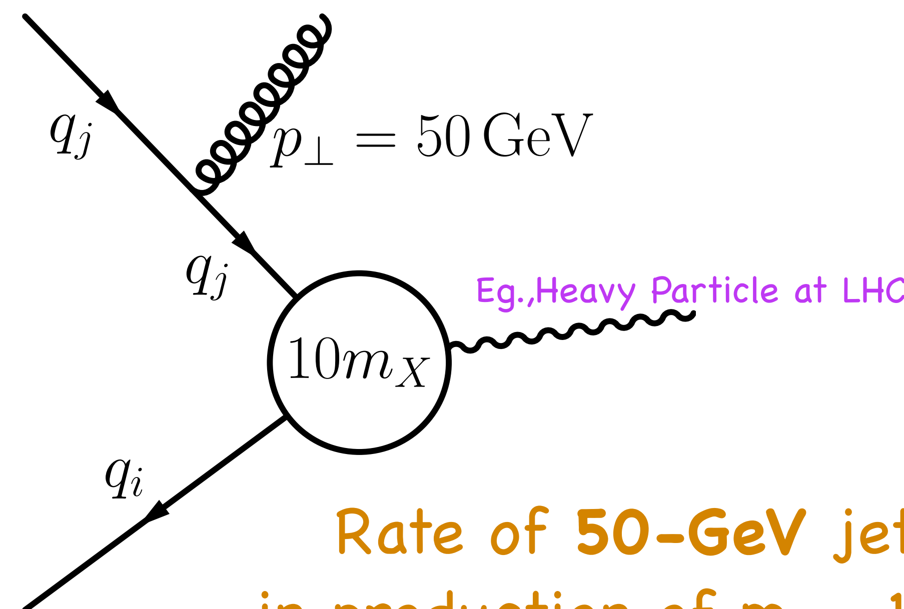
Conformal QCD (a.k.a. Bjorken scaling)

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



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

$\approx$



Rate of **50-GeV** jets
in production of $m_X = 10 m_Z$

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

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

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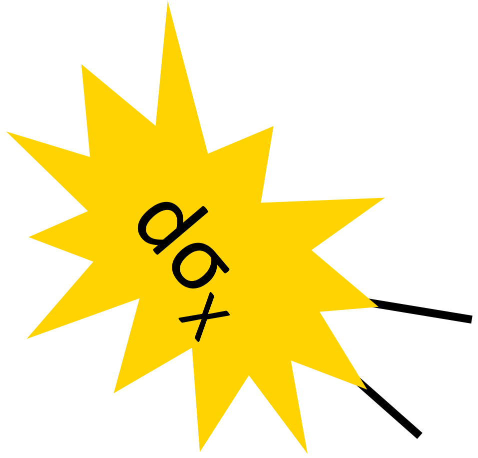
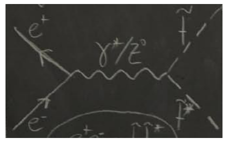
All resolved scales >> Λ_{QCD} AND X Infrared Safe

Bremsstrahlung



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

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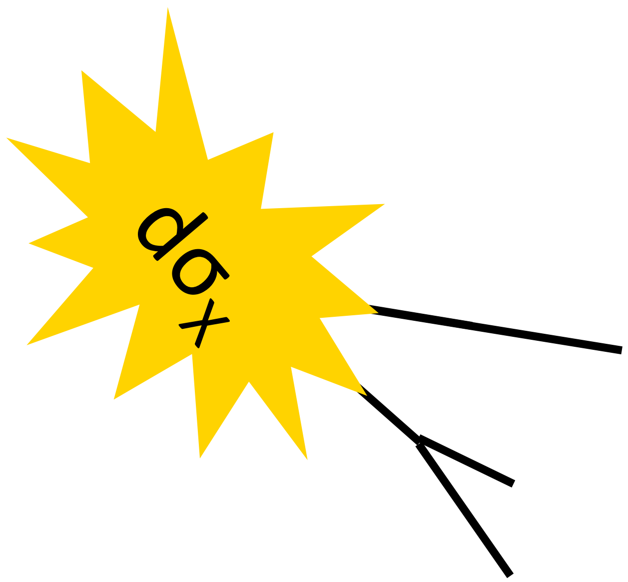
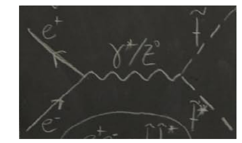


$$\mathrm{d}\sigma_X = \ldots$$ 

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

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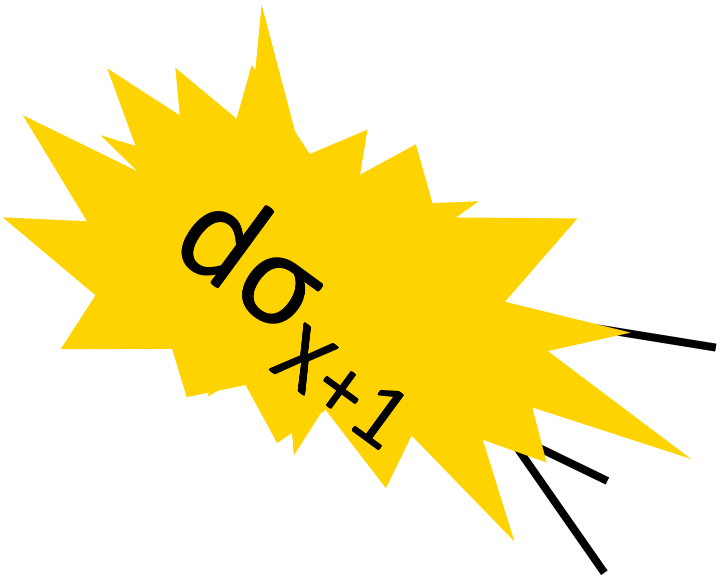

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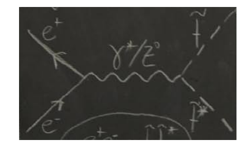

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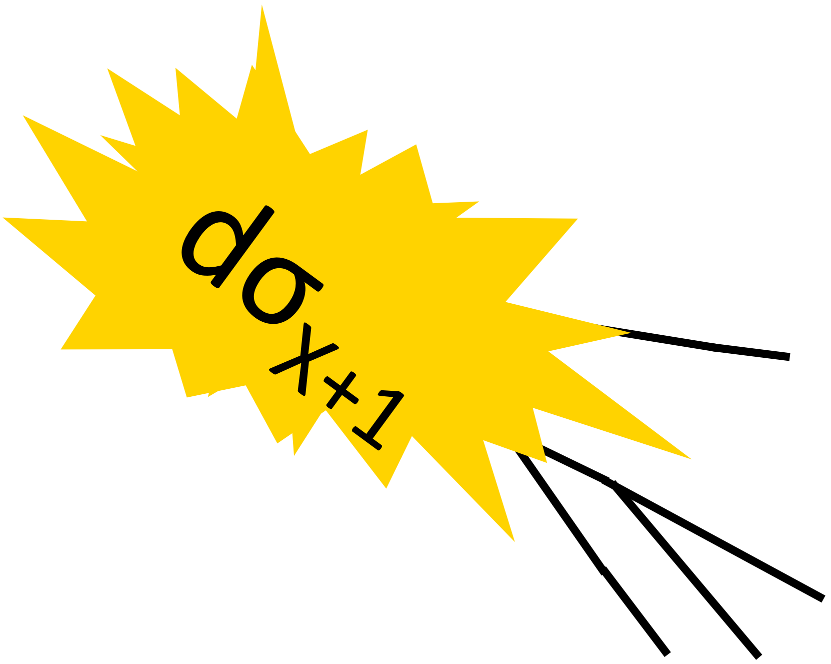
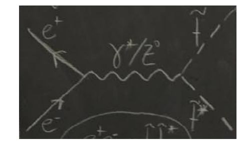


$$\mathrm{d}\sigma_X = \dots$$ 

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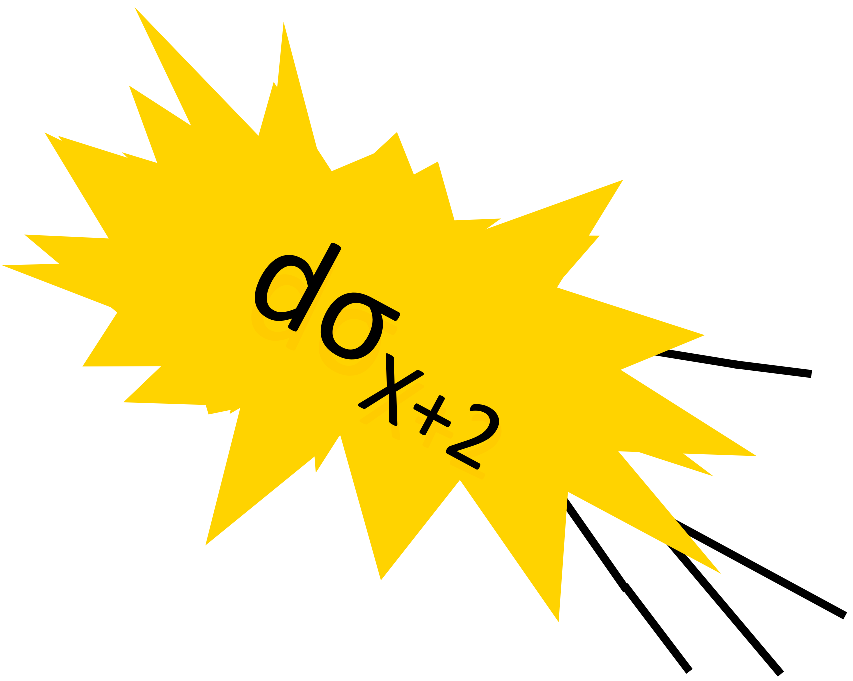
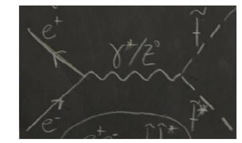


$d\sigma_X = \ldots$ 

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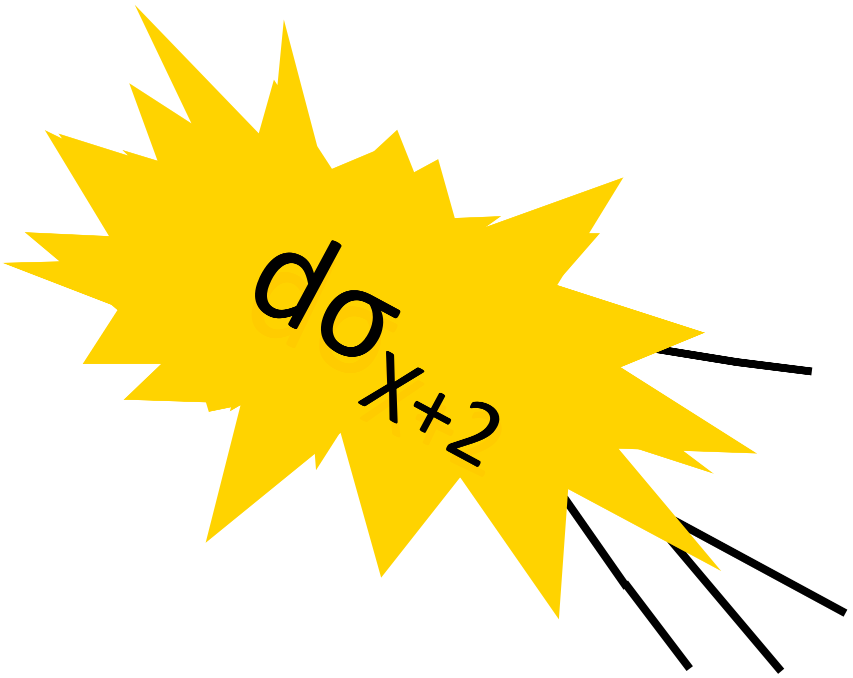
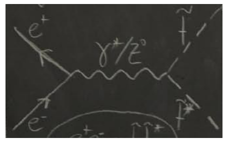


$$\mathrm{d}\sigma_X = \ldots$$ 

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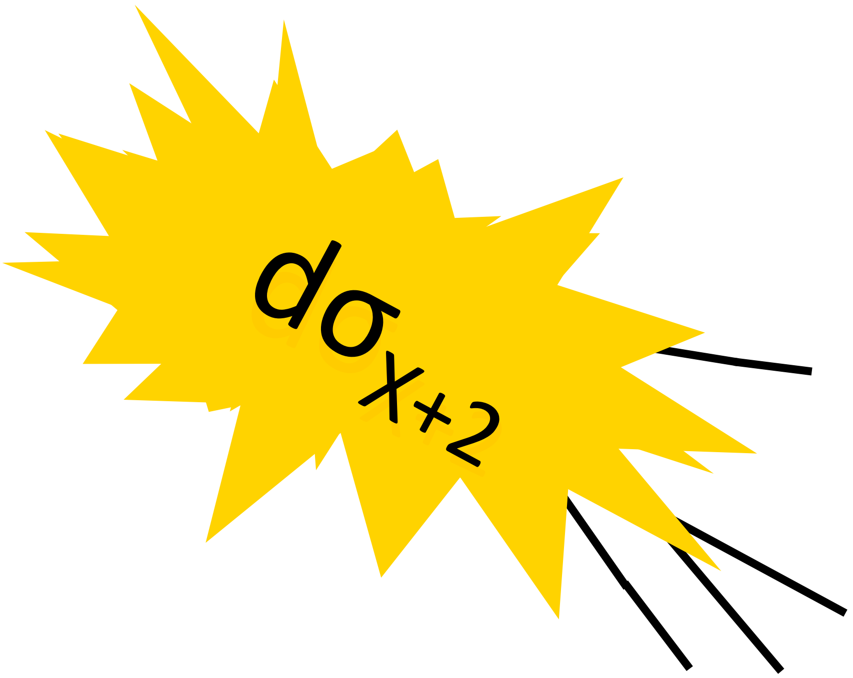
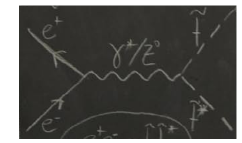


$$d\sigma_X = \ldots$$ 

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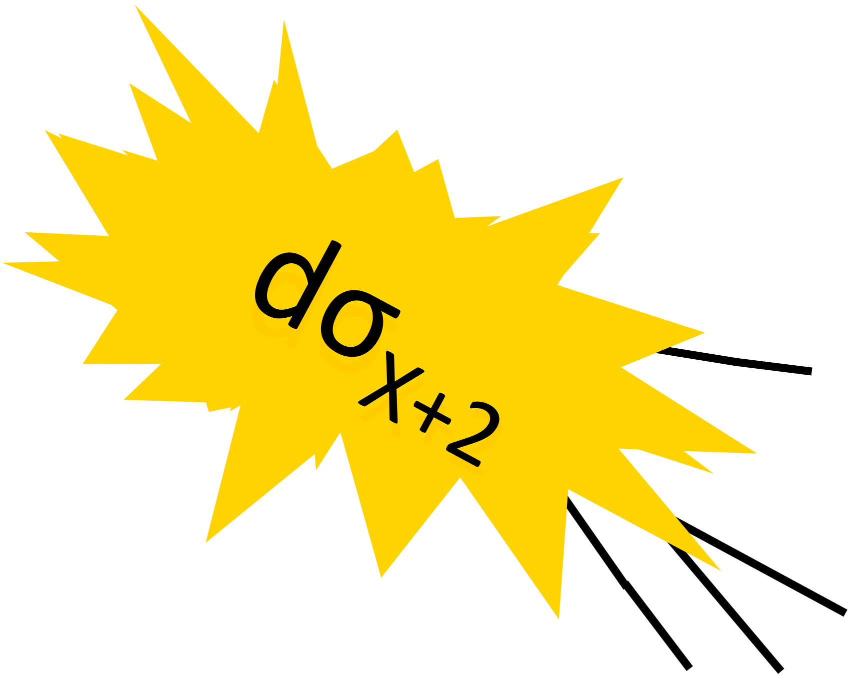
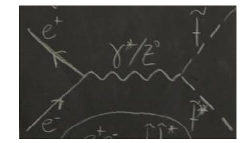
This gives an approximation to infinite-order tree-level cross sections (here "DLA")

Bremsstrahlung



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

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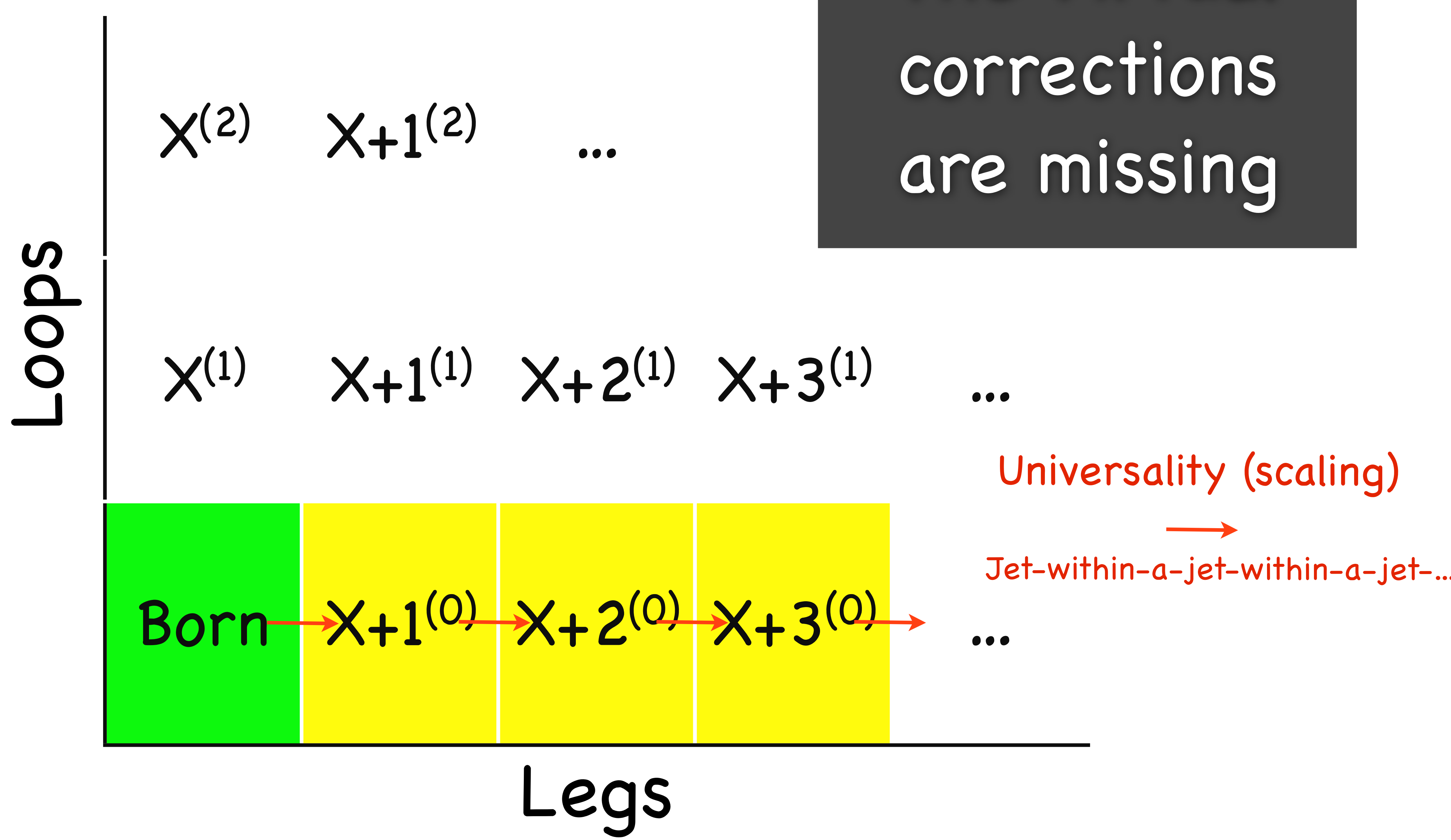
But something is not right …

Total cross section would be infinite …

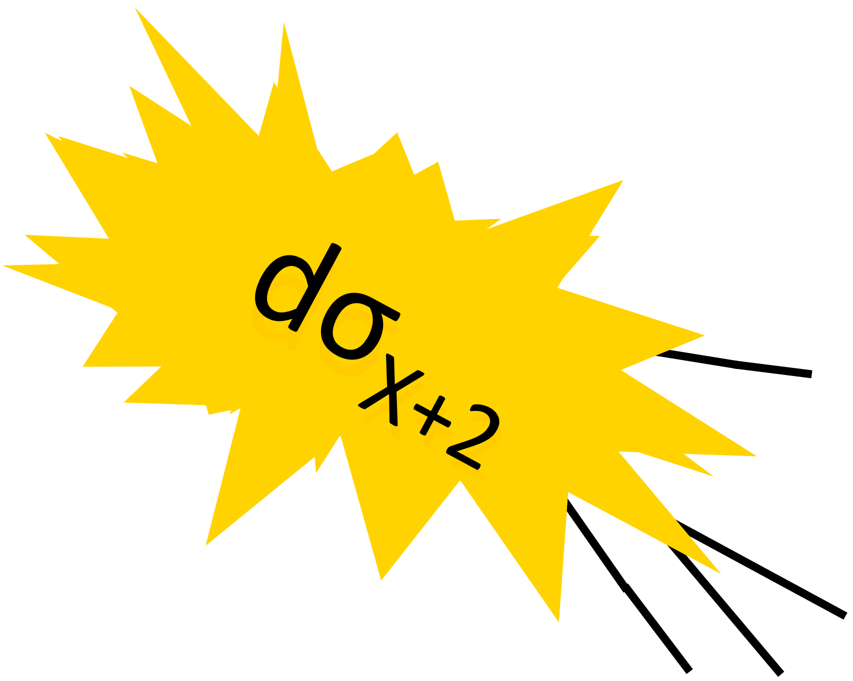
Loops and Legs

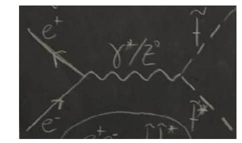
Summation

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*:

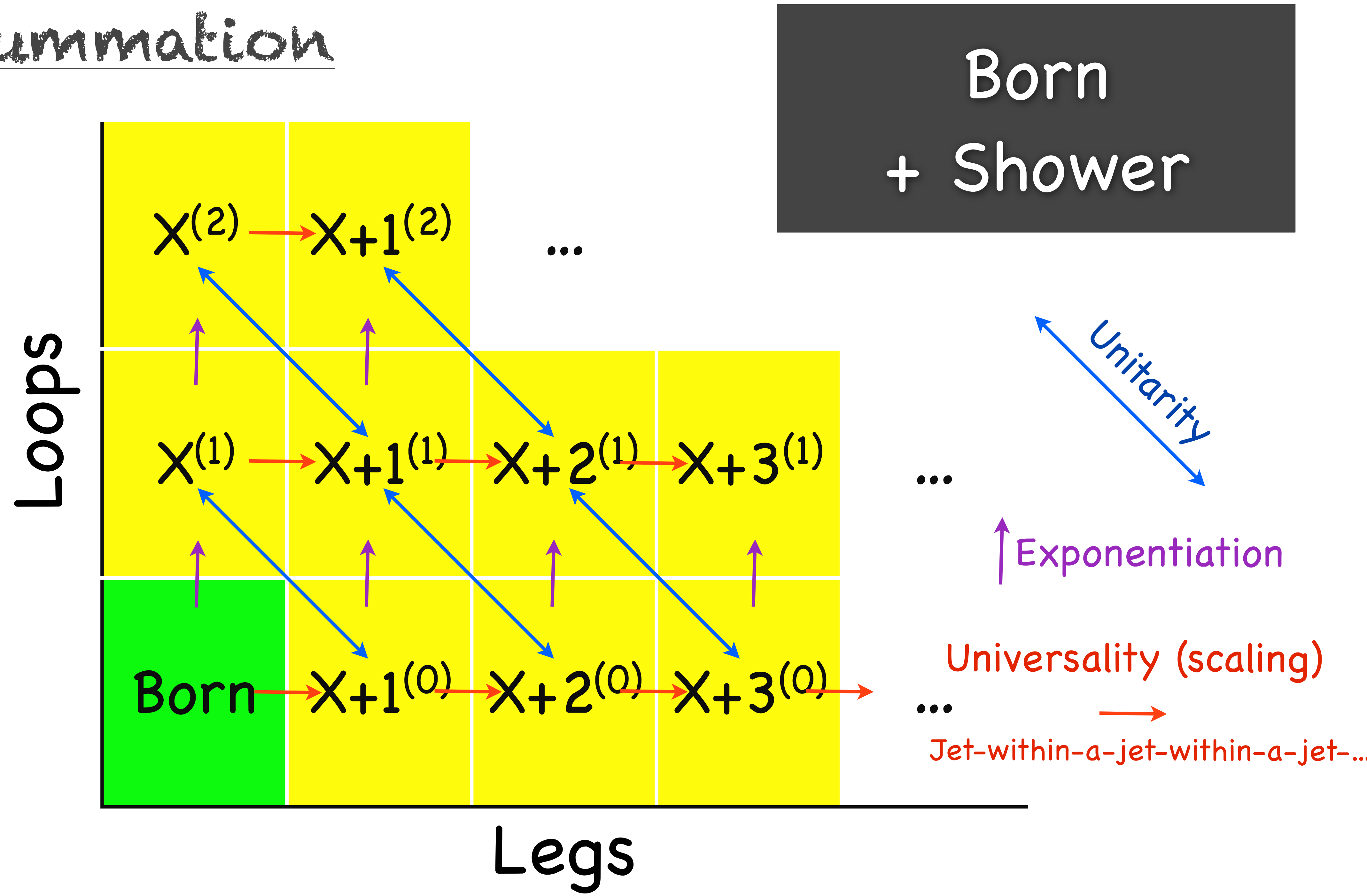
When (X) branches to (X+1):
Gain one (X+1). Loose one (X).

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

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

Bootstrapped pQCD

Resummation



Bootstrapped pQCD

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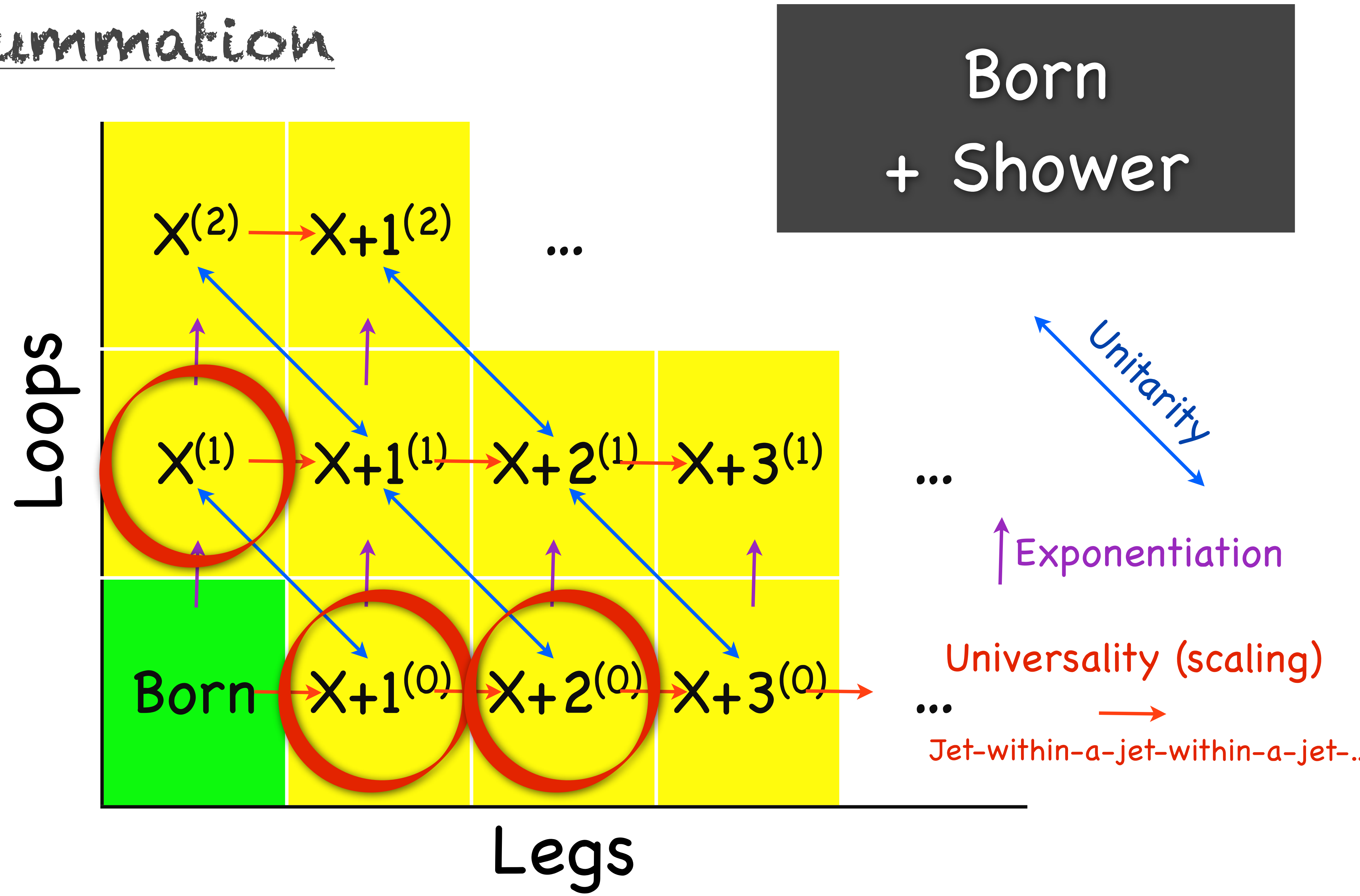

Matching

- ► A (Complete Idiot's) Solution – Combine
  1. $[X]_{ME}$ + showering
  2. $[X + 1\ jet]_{ME}$ + 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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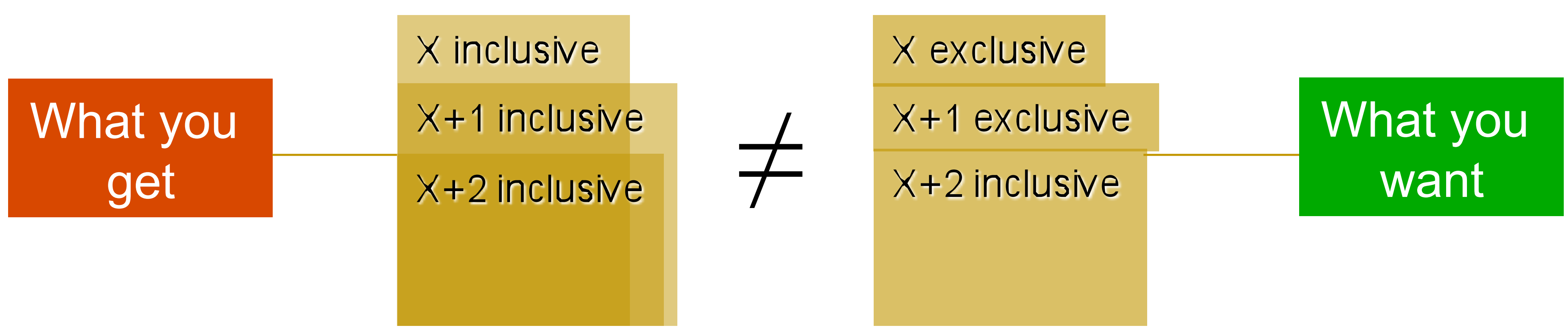
Run generator for … (+ shower)

Combine everything into one sample

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



Overlapping "bins"   One sample

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

Solution 1: "Additive" (most widespread)

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

Add event samples, with modified weights

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

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

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

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

$Q_F >> \Lambda_{QCD}$

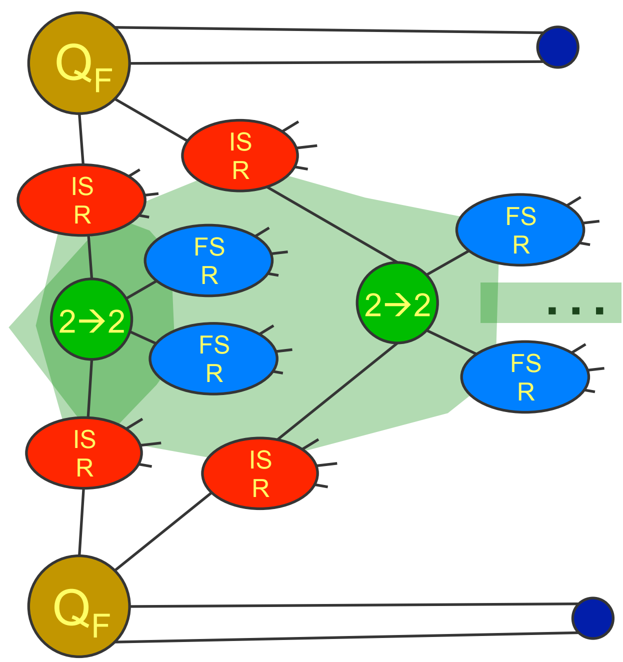
ME+ISR/FSR

+ 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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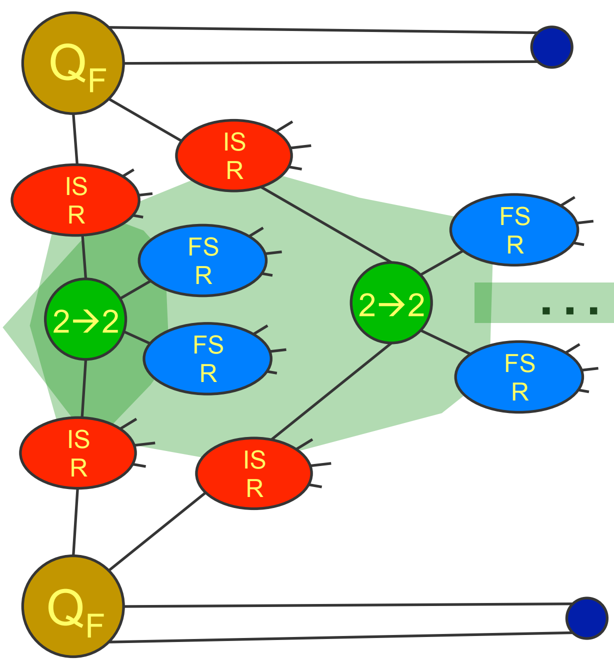

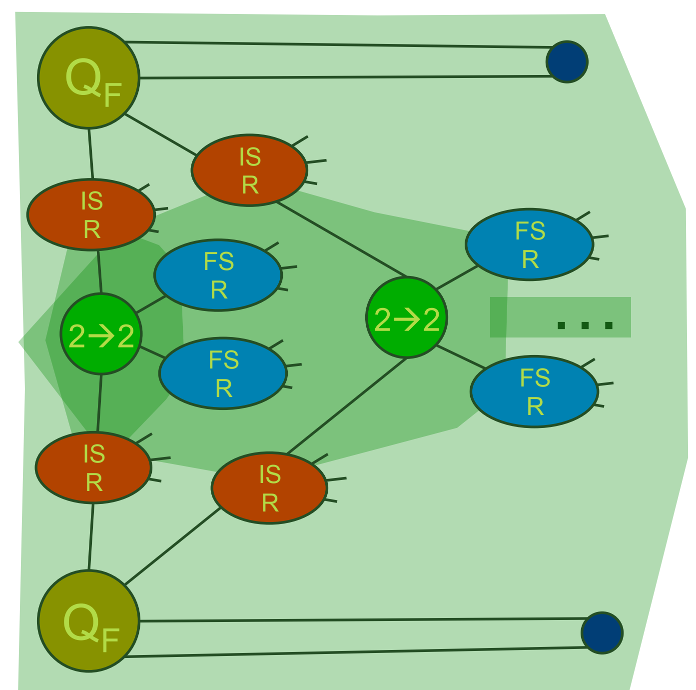

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→ **underlying event**
(distinct from pile-up caused by high lumi)

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

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_{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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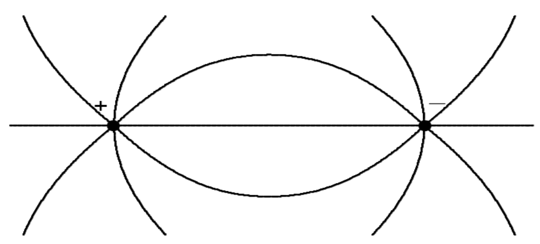
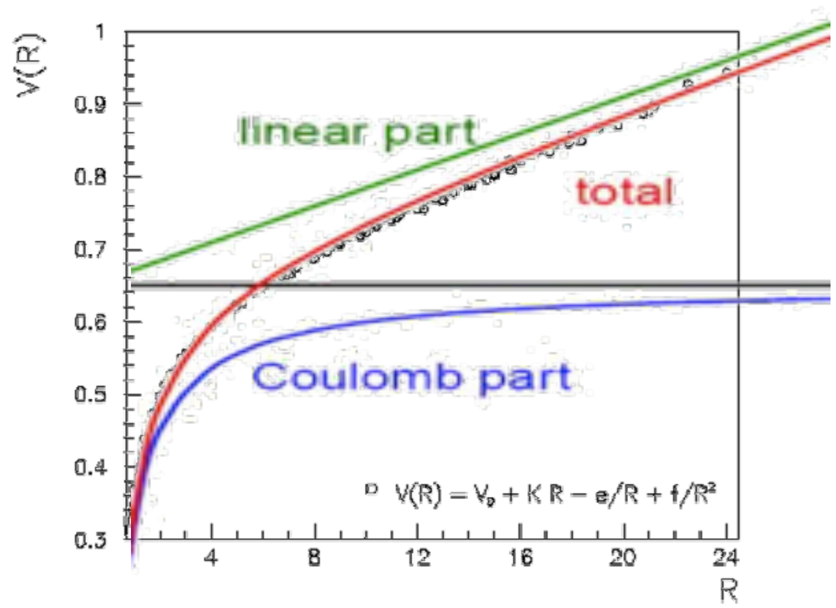
From Partons to Strings

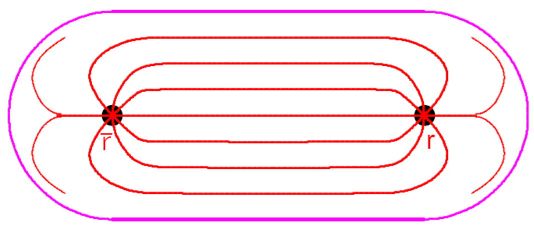
Short Distances ~ pQCD



Partons



Long Distances ~ Linear Confinement



Strings (Flux Tubes), Hadrons

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

From Partons to Strings

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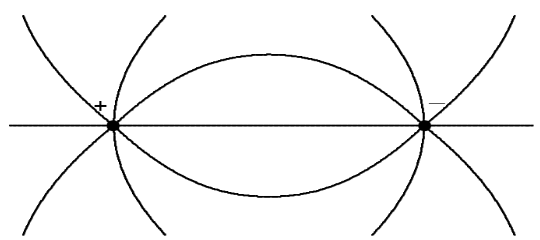
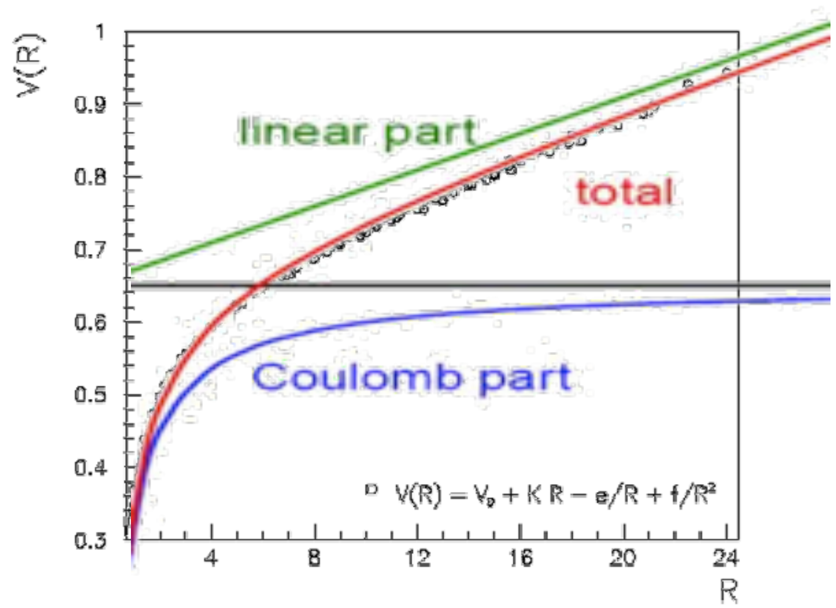


Partons



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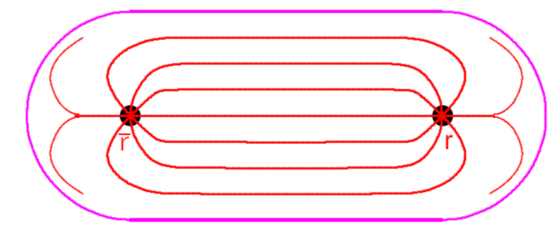


Strings (Flux Tubes), Hadrons

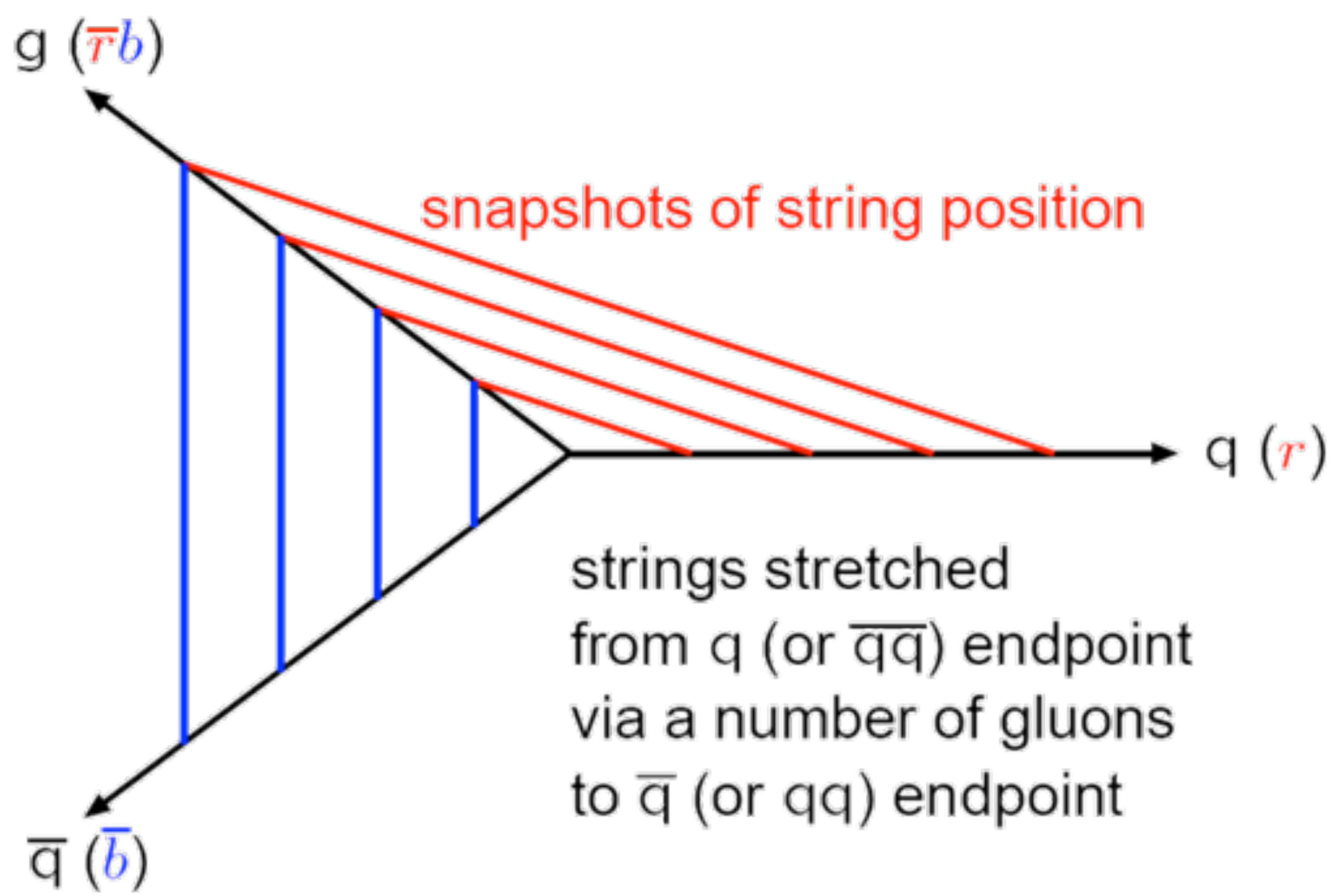
$$F(r) \approx \text{const} = \kappa \approx 1\ \text{GeV/fm} \iff V(r) \approx \kappa r$$

- **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

Conclusions

- **QCD Phenomenology** is witnessing a rapid evolution: LO & NLO matching, better showers, tuning, interfaces ...
  - Driven by demand for 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

For more, see the *MCnet* Review: General-purpose event generators for LHC physics : arXiv:1101.2599