Peter Skands
CERN TH

ALFA + ATLAS Physics Opportunities

ALFA+ATLAS Meeting, Sep 4 2012, NBI

QCD Models

A

A) Start from pQCD. Extend towards Infrared.
HERWIG/JIMMY, PYTHIA, SHERPA, EPOS

Elastic & Diffractive
Treated as separate class
Little predictivity

Color Screening
Regularization of pQCD
Hadronization

Unitarity
Showers (ISR+FSR)
Multiple 2→2 (MPI)

Quarks, Gluons
pQCD
2→2 (Rutherford)

PYTHIA uses **string fragmentation**, HERWIG & SHERPA use **cluster fragmentation**

Elastic — Min-Bias — Dijets

0 — Λ_{QCD} — 5 GeV — ∞

B

B) Start from Optical Theorem & Unitarity. Extend towards Ultraviolet.
PHOJET, DPMJET, QGSJET, SIBYLL, …

Hadrons
Optical Theorem
pp→pp

Pomerons: Diffraction
Cut Pomerons: Non-diffractive (soft)

Hard Pomeron?

Note: PHOJET & DPMJET use **string fragmentation** (from PYTHIA) → some overlap

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2→2 (Rutherford)

Strings span entire rapidity region → Constraints in forward region impact global description.

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Soft QCD: Definitions

$\sigma_{tot} \approx$		EXPERIMENT		THEORY MODELS
ELASTIC	pp→pp	QED+QCD	~	(*QED = ∞)
SINGLE DIFFRACTION	pp→p+gap+X	Fiducial region, identified proton, and/or observable gap	≠	SD model: Small gaps suppressed but not zero
DOUBLE DIFFRACTION	pp→X+gap+X		≠	DD model: Small gaps suppressed but not zero
INELASTIC NON-DIFFRACTIVE	pp→X (no gap)		≠	Large gaps suppressed but not zero

(+ multi-gap diffraction = central diff + …)

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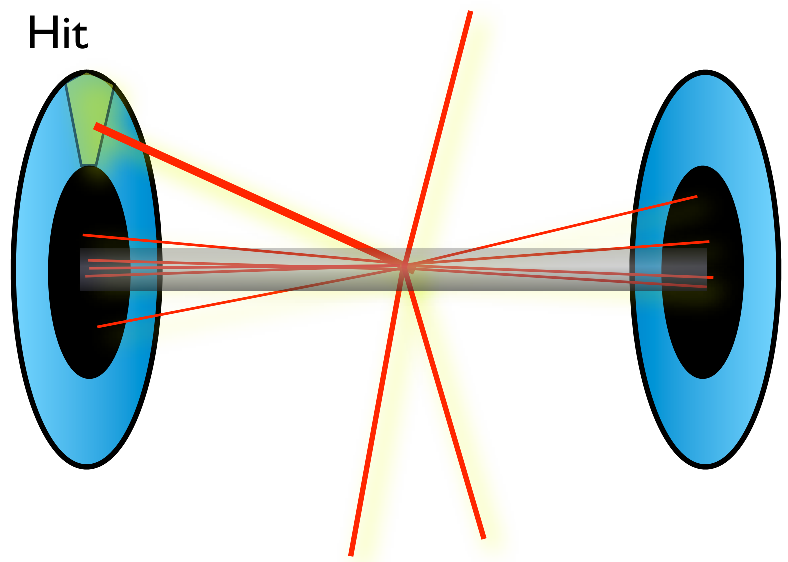


Min-Bias, Single-Gap, Forward-proton, etc.

= Experimental trigger condition(s) **(hardware-dependent)**

Correct to hardware-independent reference condition(s)

Full acceptance (not 4π), or more restrictive

"Theory" for Min-Bias/Diffraction/…?

Really = Model for ALL INELASTIC incl diffraction **(with model-dependent defs of ND, SD, …)**

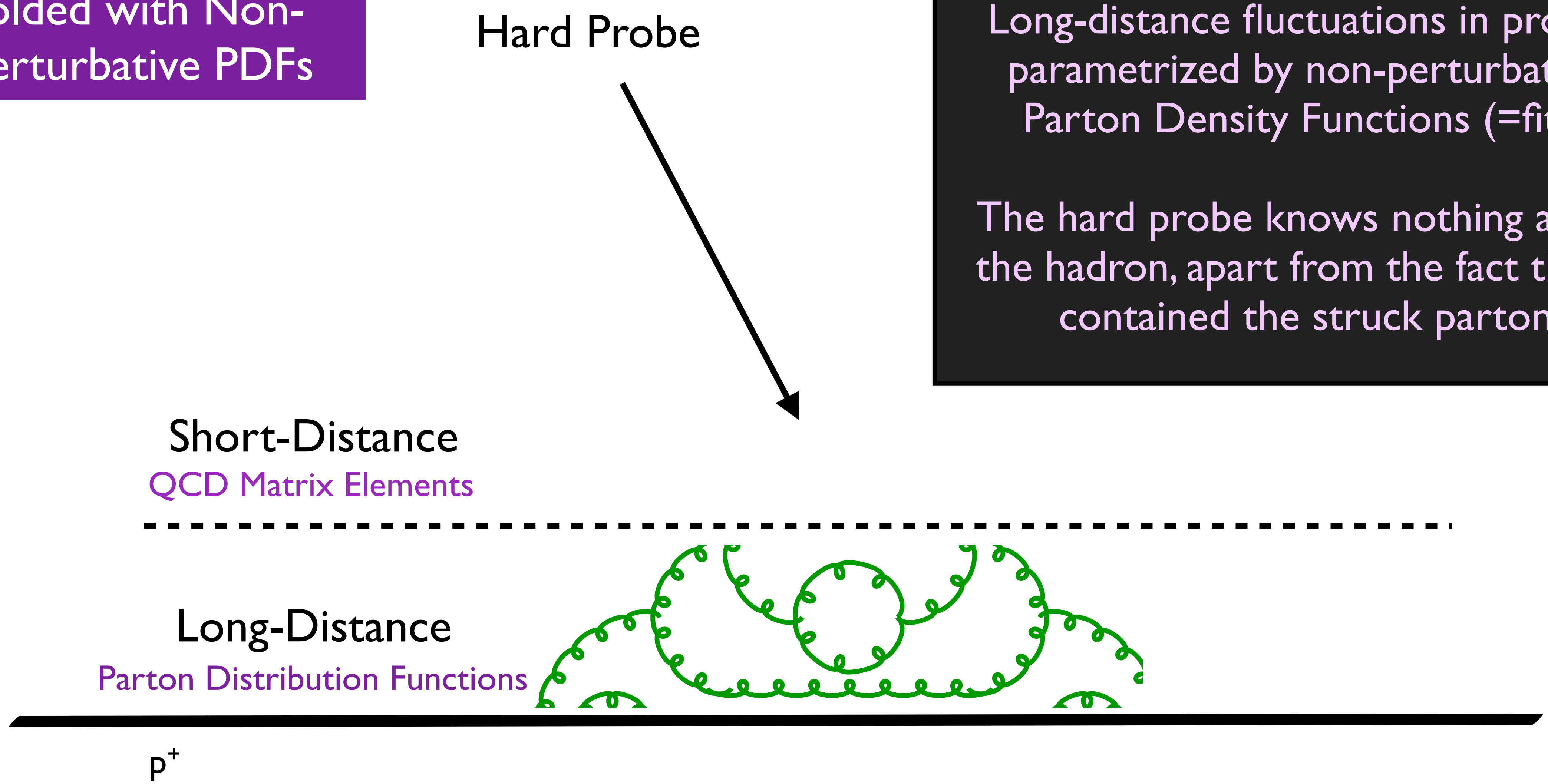
Compare to data with different reference condition(s) → suppress/enhance diffraction

Can also extrapolate to full phase space **(model-dependent)**

1) Hard Interactions

(Inelastic, Non-Diffractive)

Perturbative QCD folded with Non-Perturbative PDFs



<u>Factorization</u>:

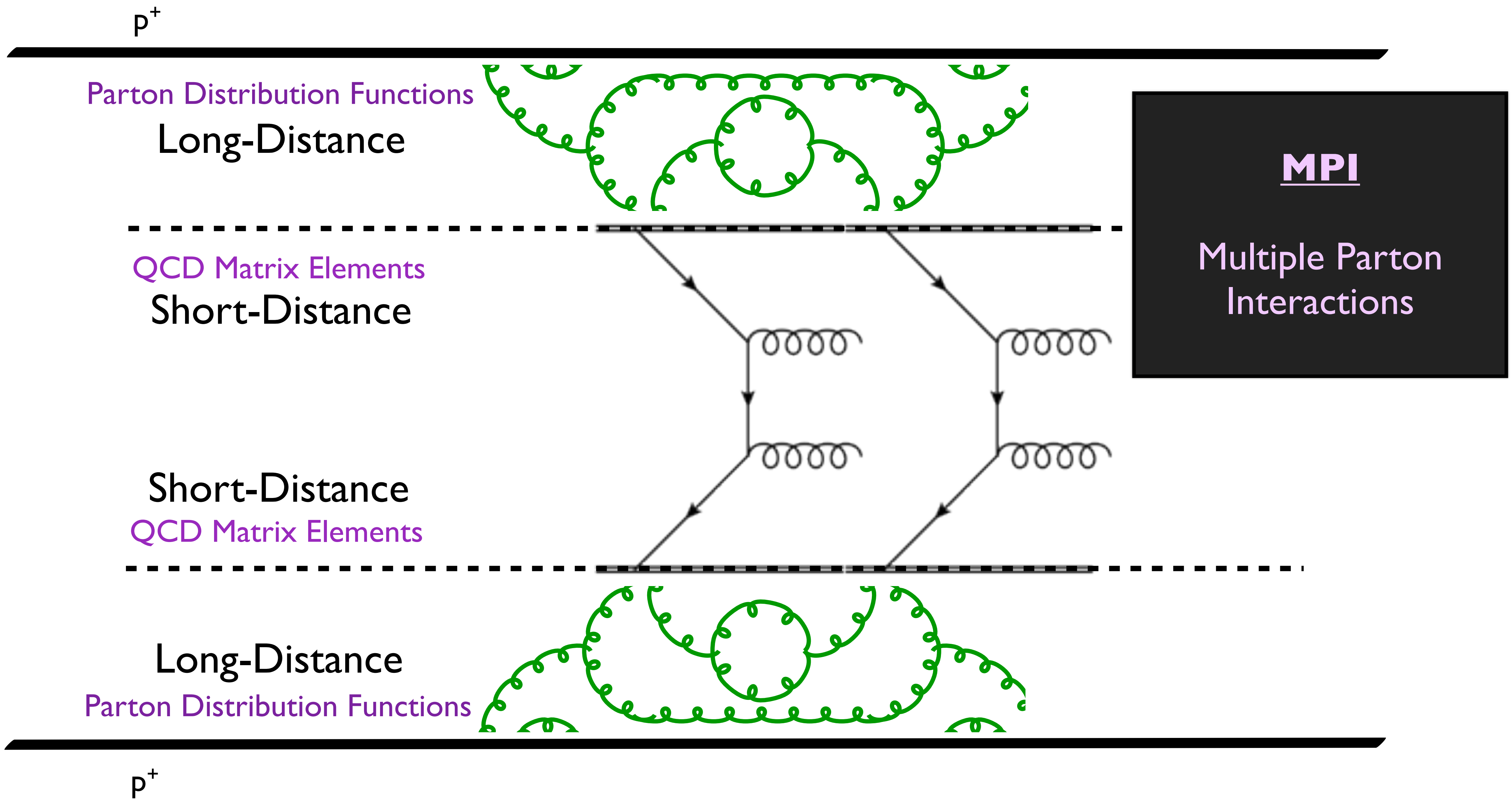
Long-distance fluctuations in proton parametrized by non-perturbative Parton Density Functions (=fits)

The hard probe knows nothing about the hadron, apart from the fact that it contained the struck parton

2) Underlying Event (UE)

(A.K.A. the "Pedestal Effect")

Hadrons are composite → possibility of Multiple Simultaneous Parton Interactions



***Example**: two parton-parton interactions in one pp interaction*

→ Generates UE > Min-Bias (& destroys diffractive gaps)

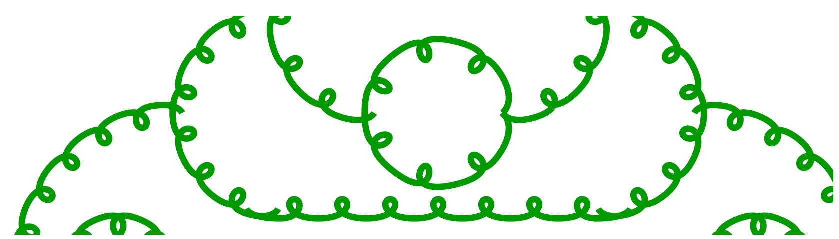
3) Diffraction

(Hitting Colour-Singlet Substructure Fluctuations in the Beam Hadrons)

Full hadron wavefunction
contains a superposition of states

Short-Distance

Long-Distance



Very Long-Distance
$Q < \Lambda$

p^+ p^+

3) Diffraction

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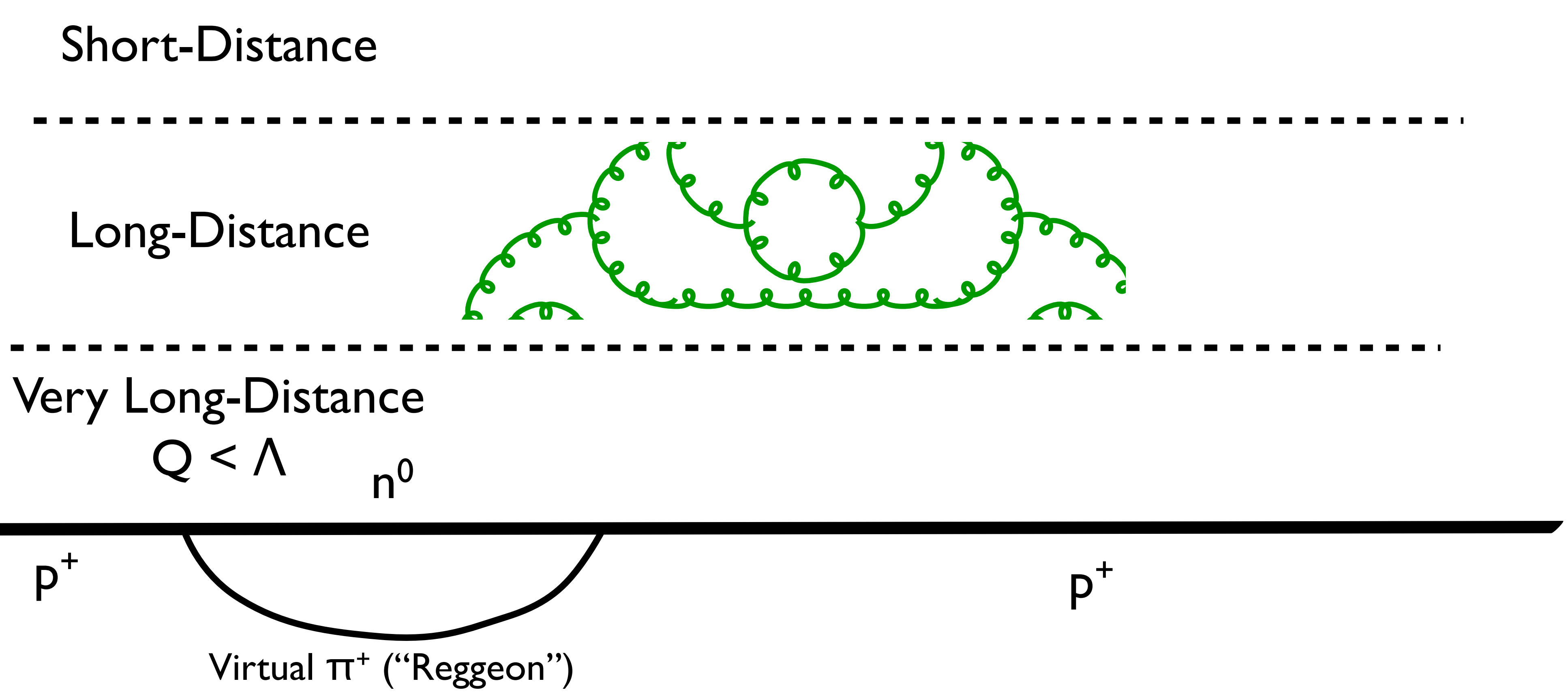
→ Sometimes, $p = n^0\pi+$ for a little (virtual) while …



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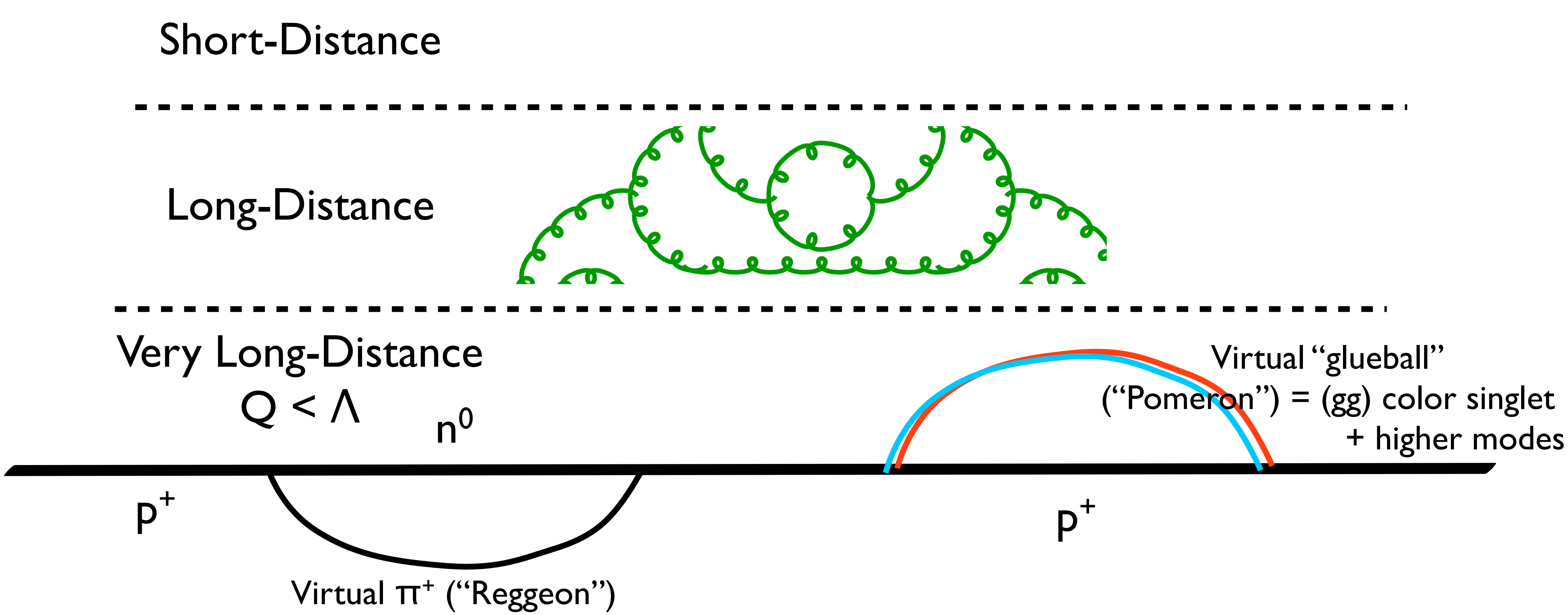
… etc …



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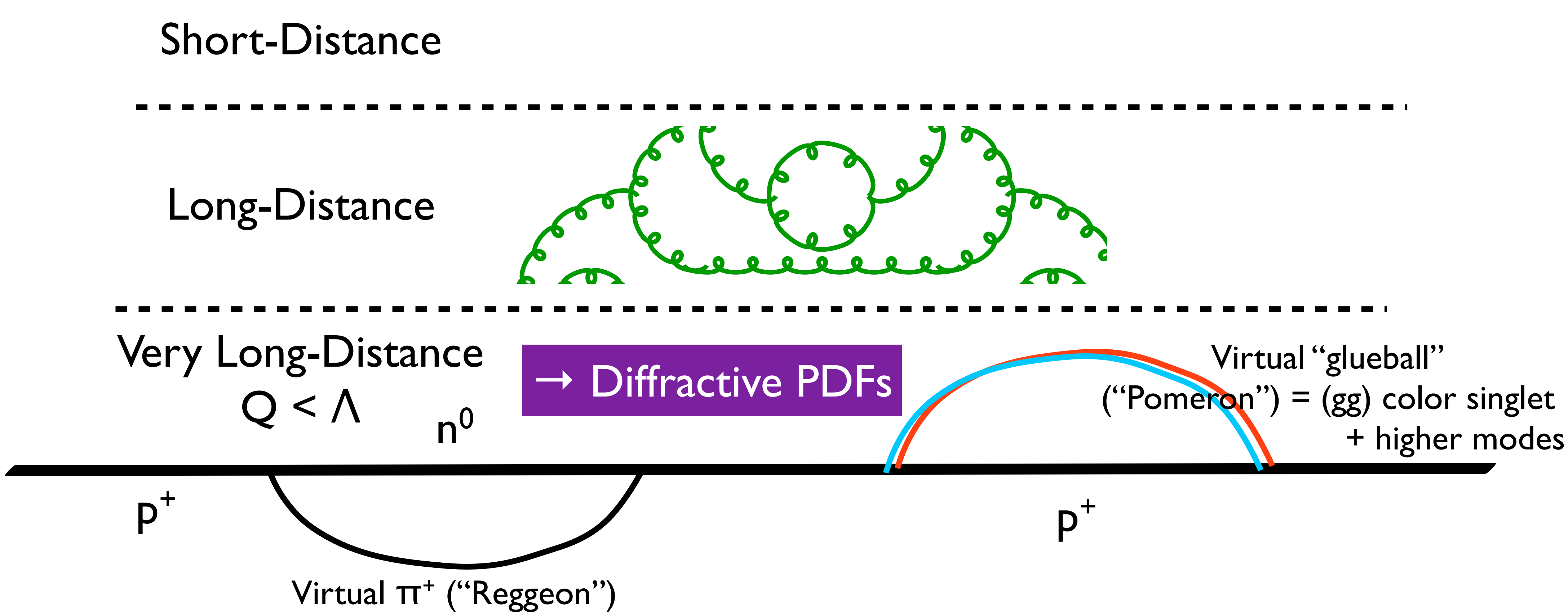
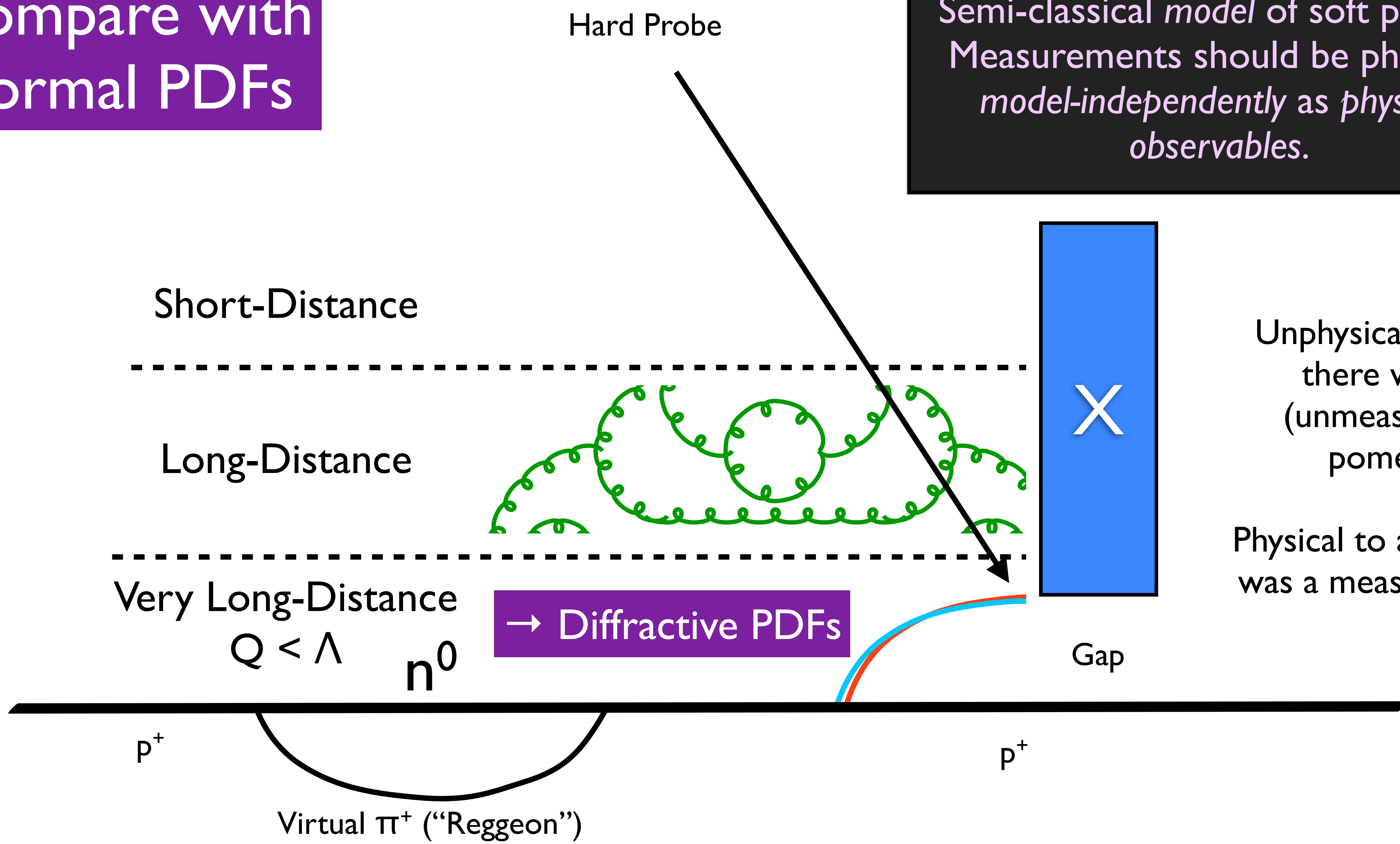


3) Diffraction

(Colour-Singlet Substructure Fluctuations in the Beam Hadrons)

Compare with normal PDFs

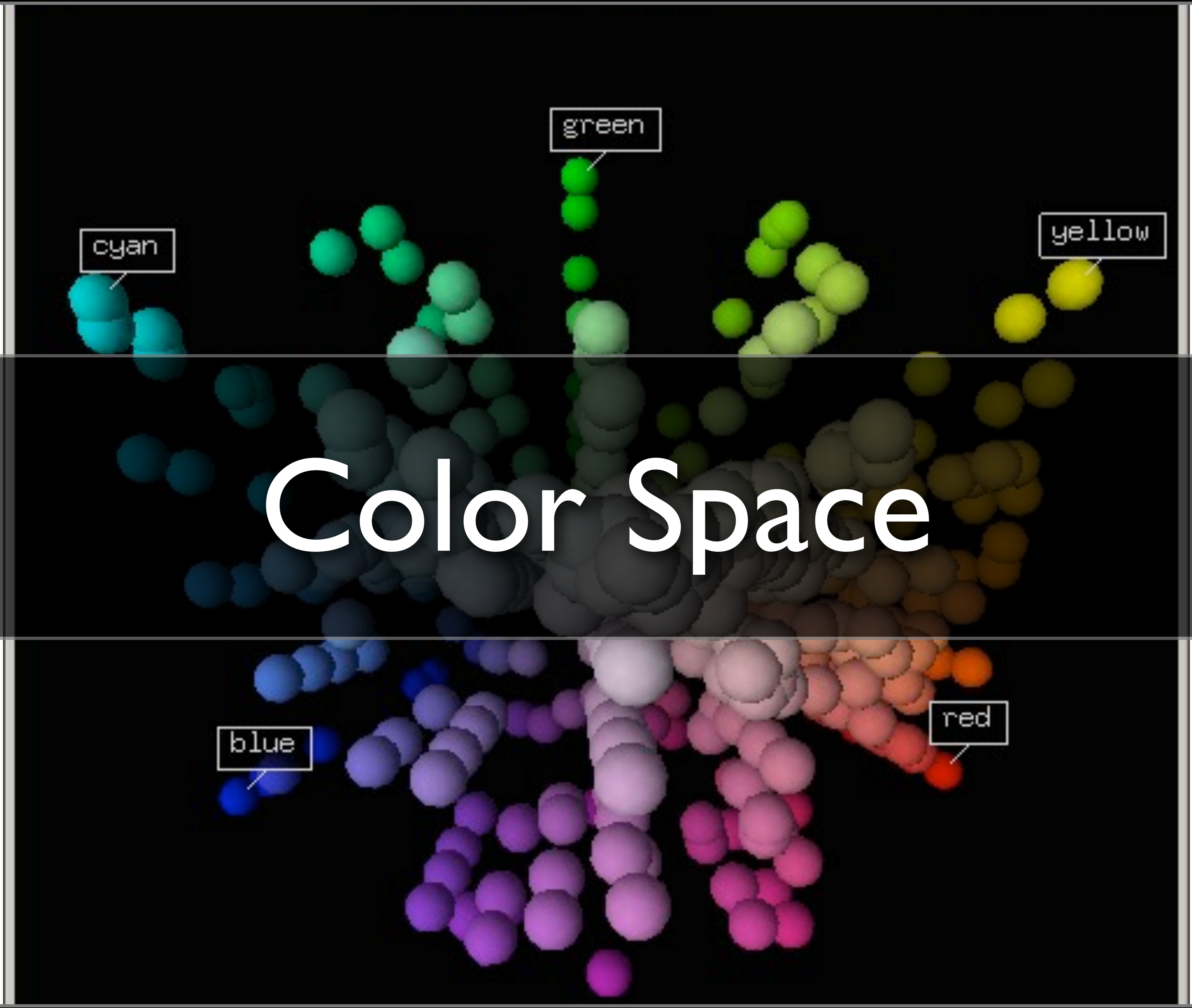
<u>Note on Diffraction:</u>
Traditionally phrased in the language of Regge "Theory" = Semi-classical *model* of soft physics. Measurements should be phrased *model-independently* as *physical observables*.



Unphysical to ask if there was an (unmeasurable) pomeron

Physical to ask if there was a measurable gap

Color Space

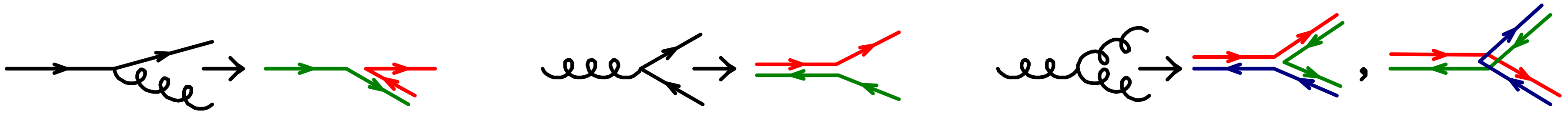


Color Flow in MC Models

"Planar Limit"

Equivalent to $N_C \to \infty$: no color interference*

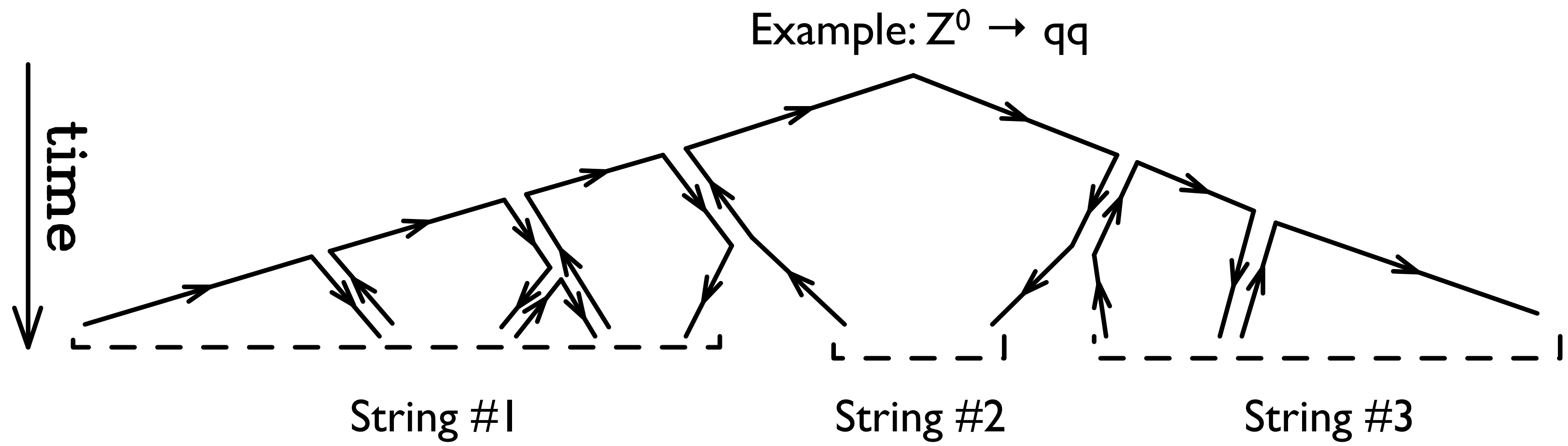
Rules for color flow:



*) except as reflected by the implementation of QCD coherence effects in the Monte Carlos via angular or dipole ordering

For an entire cascade:

Illustrations from: Nason + PS, PDG Review on *MC Event Generators*, 2012



Coherence of pQCD cascades → not much "overlap" between strings

→ planar approx pretty good

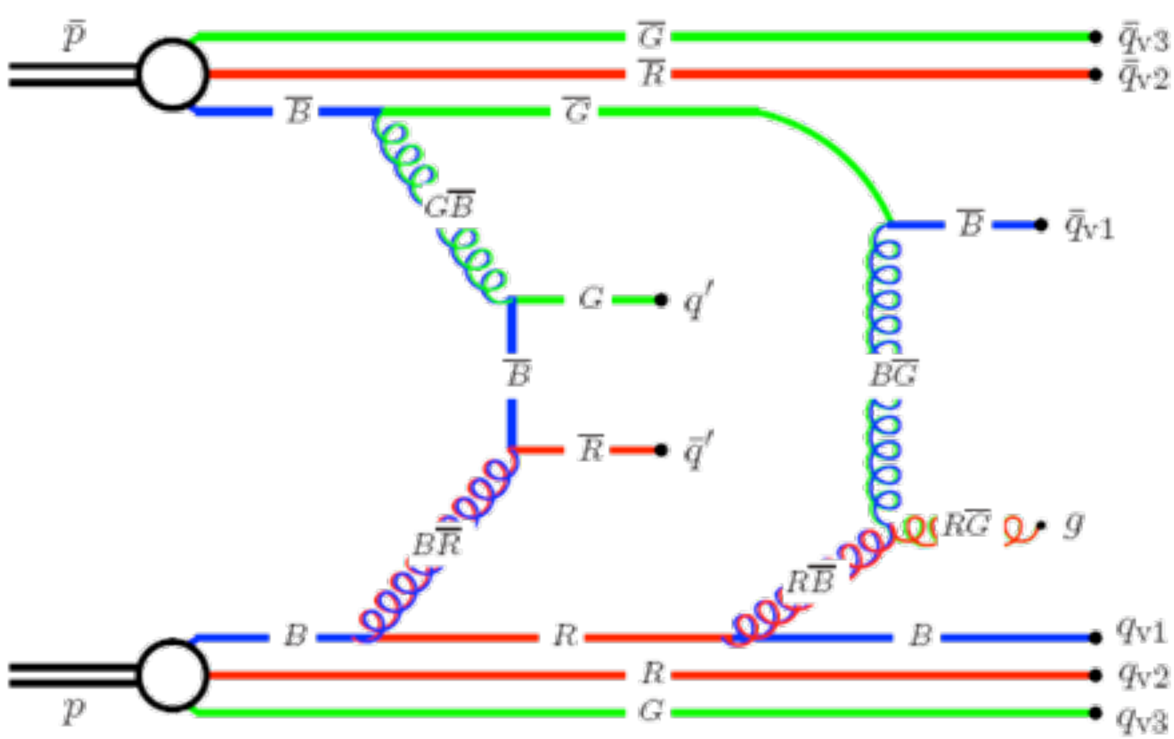
LEP measurements in WW confirm this (at least to order 10% ~ $1/N_c^2$)

Color Connections

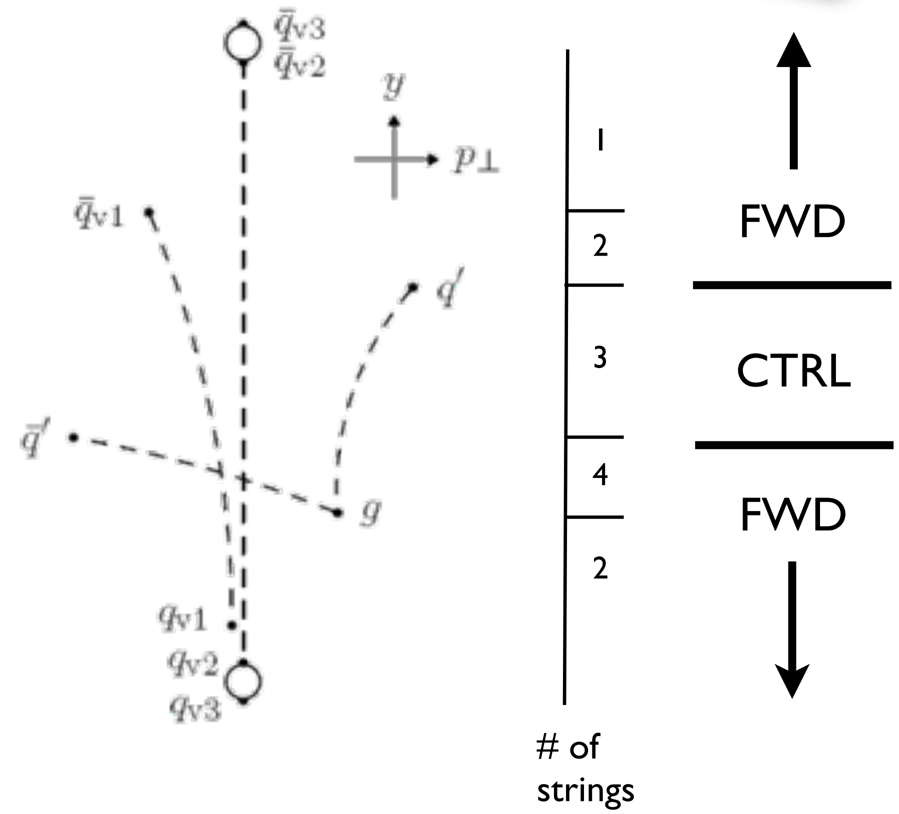
Each MPI (or cut Pomeron) exchanges color between the beams

- ▶ The colour flow determines the hadronizing string topology
  - Each MPI, even when soft, is a color spark
  - Final distributions crucially depend on color space

Different models make different ansätze



Sjöstrand & PS, JHEP 03(2004)053



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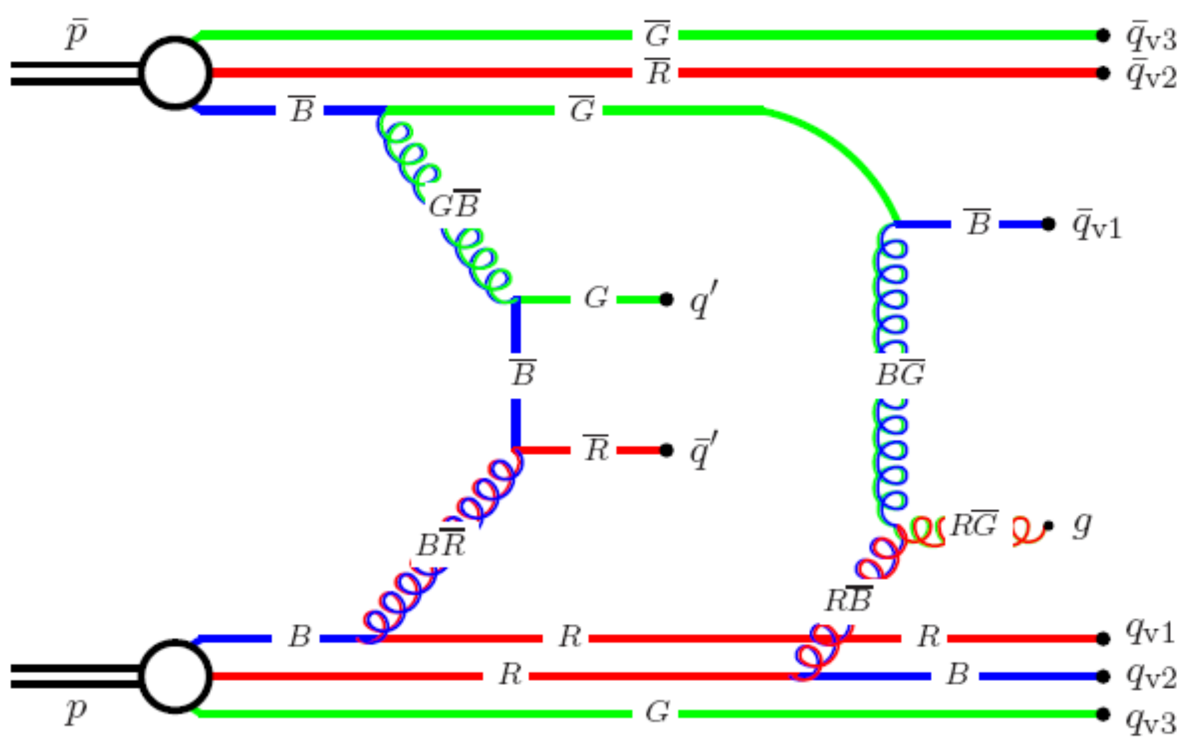

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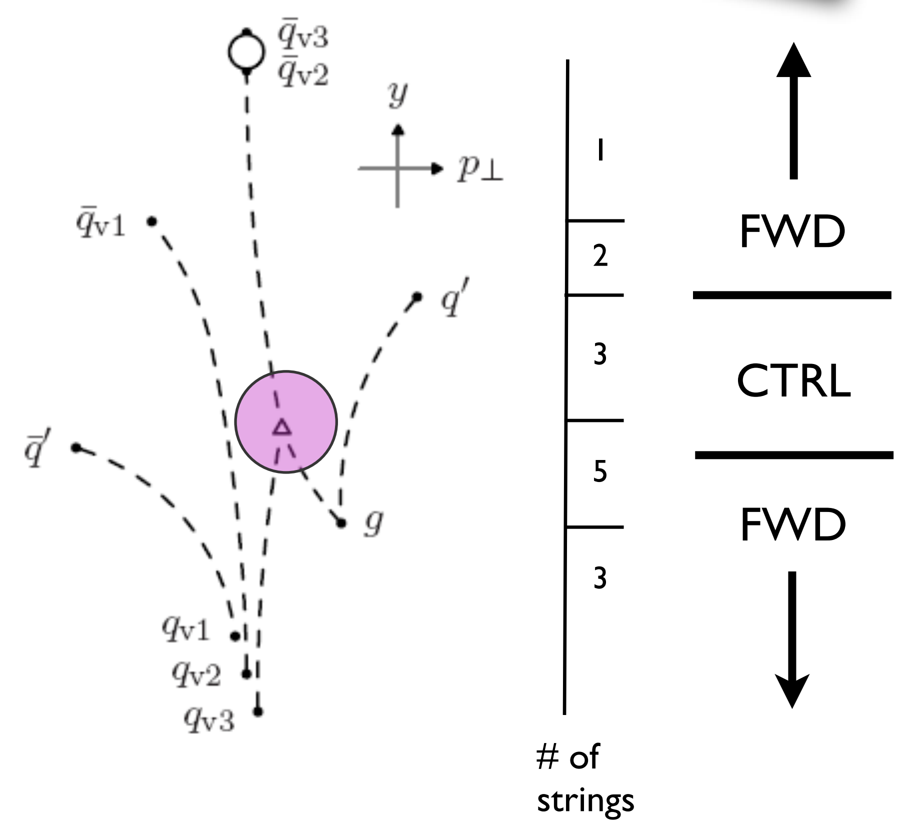
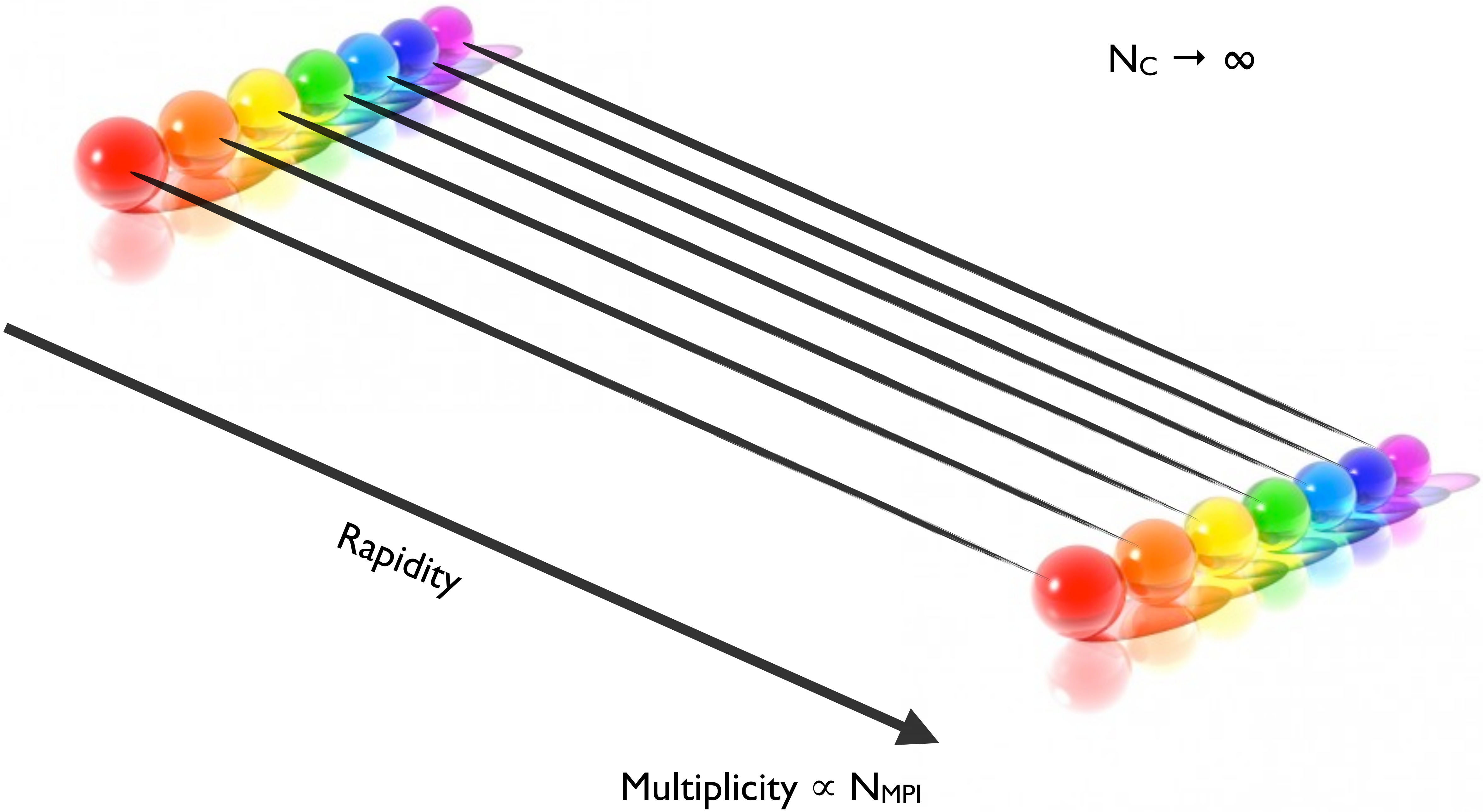


Color Connections

Better theory models needed

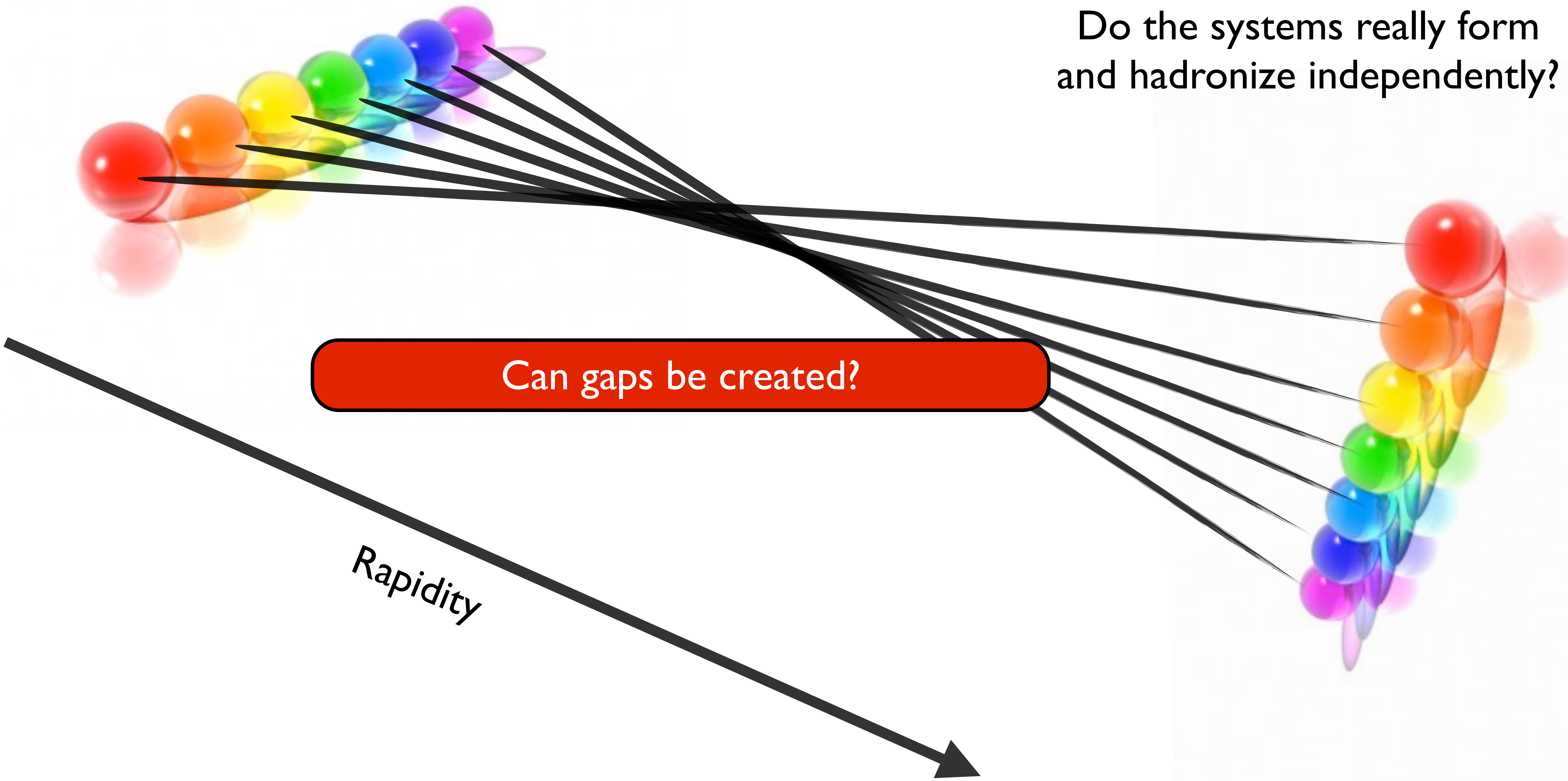


Color Reconnections?

E.g.,
Generalized Area Law (Rathsman: Phys. Lett. B452 (1999) 364)
Color Annealing (P.S., Wicke: Eur. Phys. J. C52 (2007) 133)
Statistical CR (Gieseke et al., arXiv:1206004)

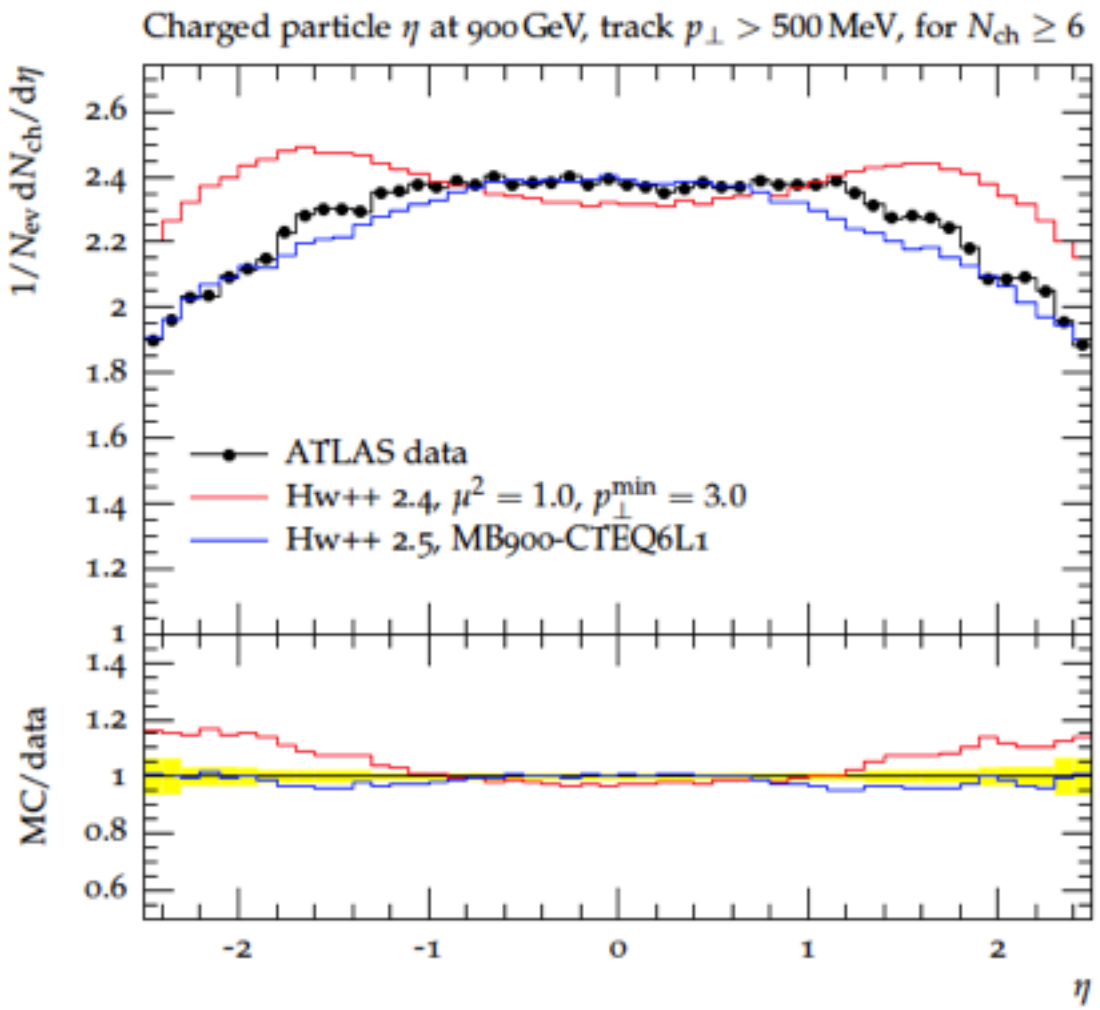
Better theory models needed

Do the systems really form
and hadronize independently?

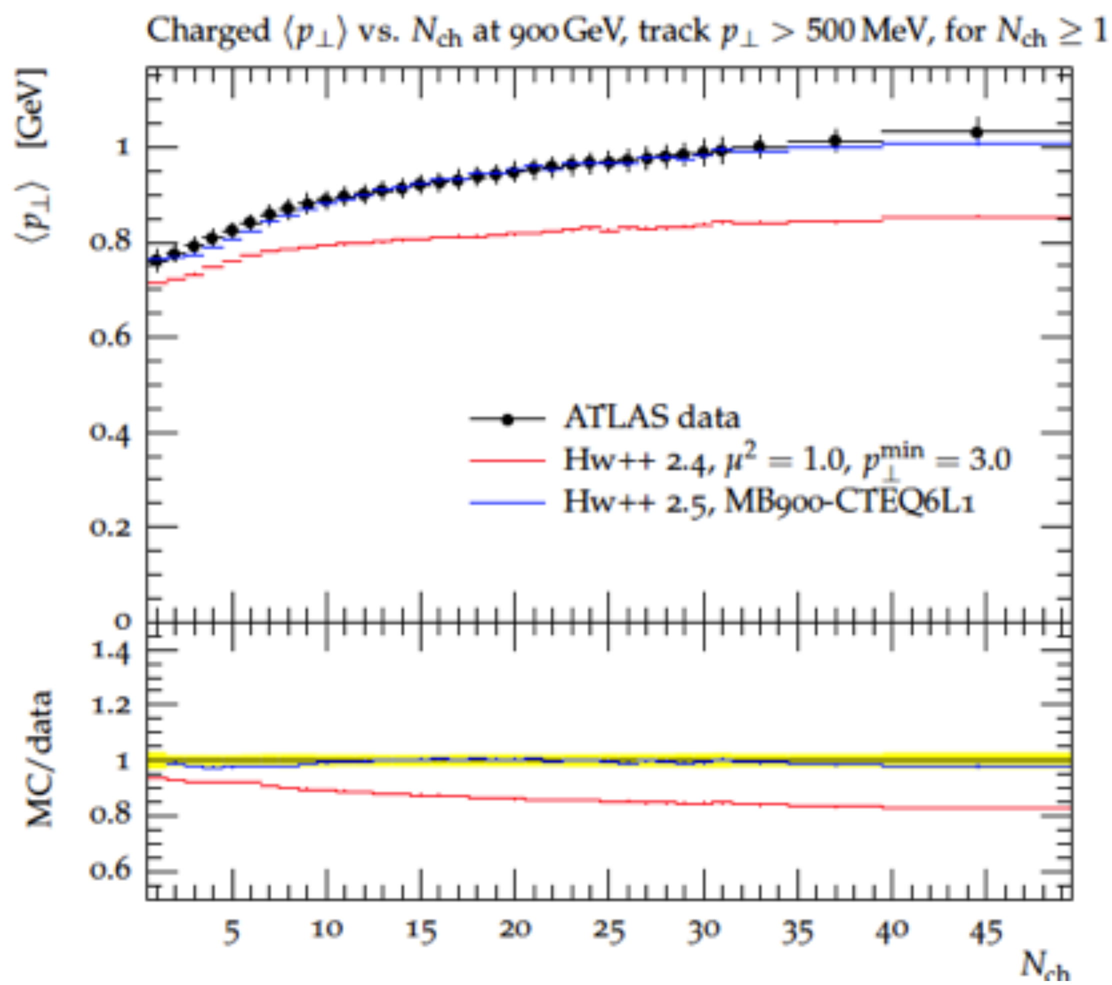


Multiplicity $\overset{<}{\not\propto} N_{MPI}$

Examples from "CR in Herwig++" : Gieseke et al., arXiv:1206004
(Note: exhibits larger dN/dη effects than PYTHIA models, but qualitative features similar)



Forward region becomes less active



Average track pT becomes higher

Min-Bias & Underlying Event

Main IR Parameters

Number of MPI

Pedestal Rise

Strings per Interaction

Min-Bias & Underlying Event

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Infrared Regularization scale for the QCD 2→2 (Rutherford) scattering used for multiple parton interactions (often called p_{T0}) → size of overall activity

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Proton transverse mass distribution → difference betwen central (active) vs peripheral (less active) collisions

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Strings per Interaction

Color correlations between multiple-parton-interaction systems → shorter or longer strings → less or more hadrons per interaction

+ Diffraction (in PYTHIA 8)

Navin, arXiv:1005.3894

Diffractive Cross Section Formulæ:

$$\frac{d\sigma_{sd(AX)}(s)}{dt\, dM^2} = \frac{g_{3\mathbb{P}}}{16\pi}\, \beta_{A\mathbb{P}}^2\, \beta_{B\mathbb{P}}\, \frac{1}{M^2}\, \exp(B_{sd(AX)}t)\, F_{sd} \,,$$

$$\frac{d\sigma_{dd}(s)}{dt\, dM_1^2\, dM_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\, \beta_{A\mathbb{P}}\, \beta_{B\mathbb{P}}\, \frac{1}{M_1^2}\, \frac{1}{M_2^2}\, \exp(B_{dd}t)\, F_{dd} \,.$$

$M_X \leq$ 10 GeV (and for all masses in PYTHIA 6)

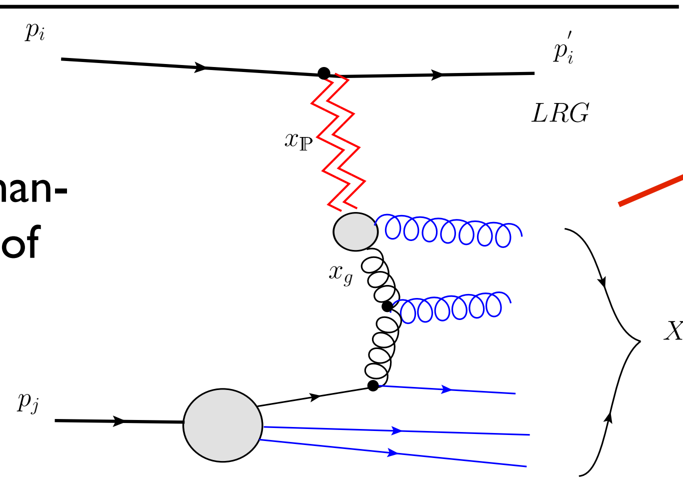
Represent M_X as longitudinal string → Fragment

→ Typical string-fragmentation spectrum

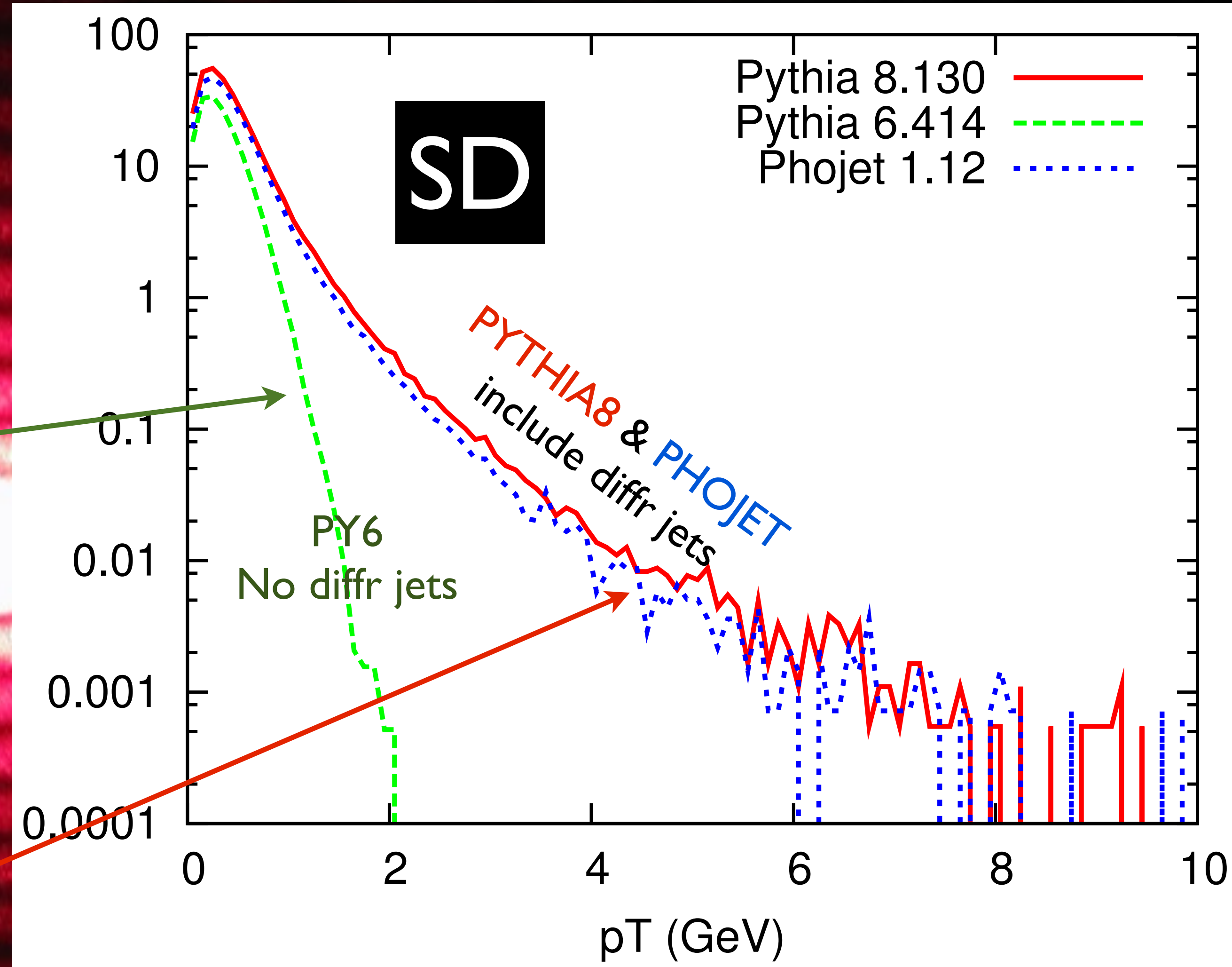
Partonic Substructure in Pomeron:

M_X > 10 GeV

Follows the Ingelman-Schlein approach of Pompyt



PYTHIA 8



+ NEW! full MPI + showers for $\mathbb{P}$p system (→ UE in Diffraction)
+ NEW! Central Diffraction (→ fully contained gap-X-gap events)
+ NEW! Alternative Min-Bias Rockefeller (MBR) Model

Choice between 5 Pomeron PDFs.

+ Recently Central Diffraction!

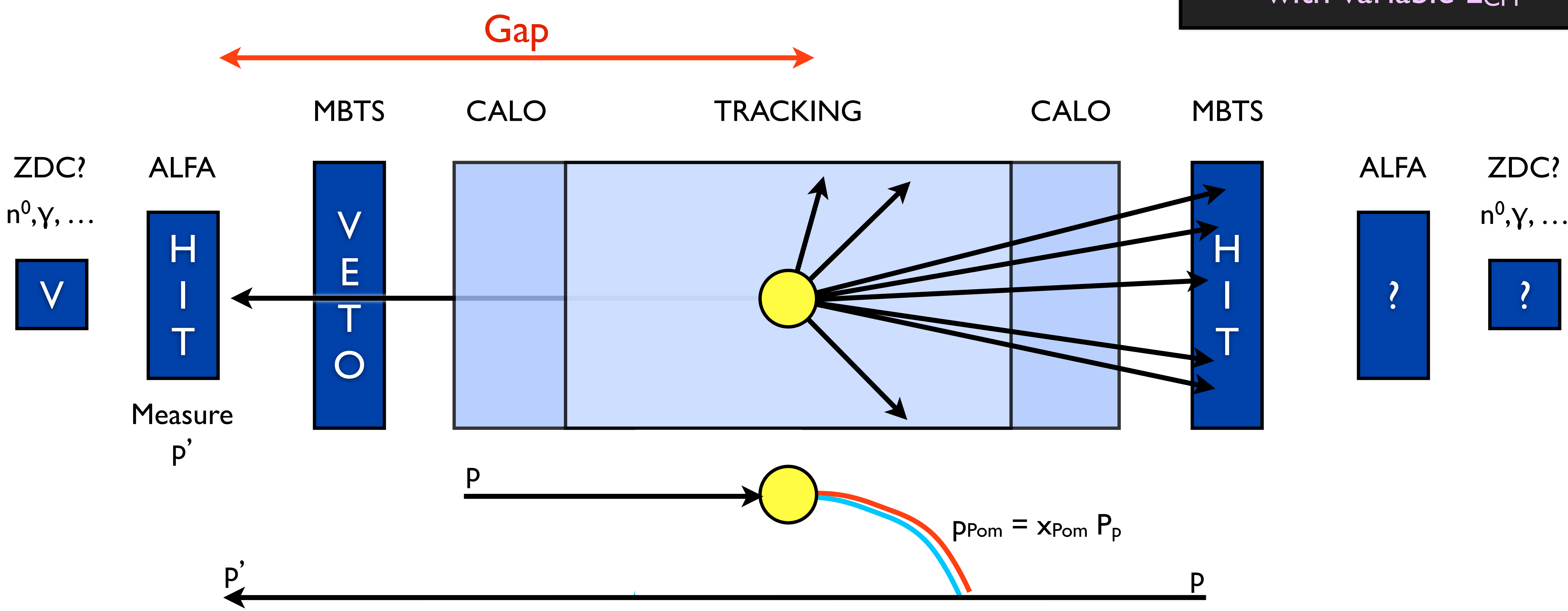
Free parameter $\sigma_{\mathbb{P}p}$ needed to fix $\langle n_{\text{interactions}} \rangle = \sigma_{\text{jet}}/\sigma_{\mathbb{P}p}$.

Framework needs testing and tuning, e.g. of $\sigma_{\mathbb{P}p}$.

(Some) Opportunities with ALFA + ATLAS

Single Diffraction

Glueball-Proton Collider with variable E_{CM}



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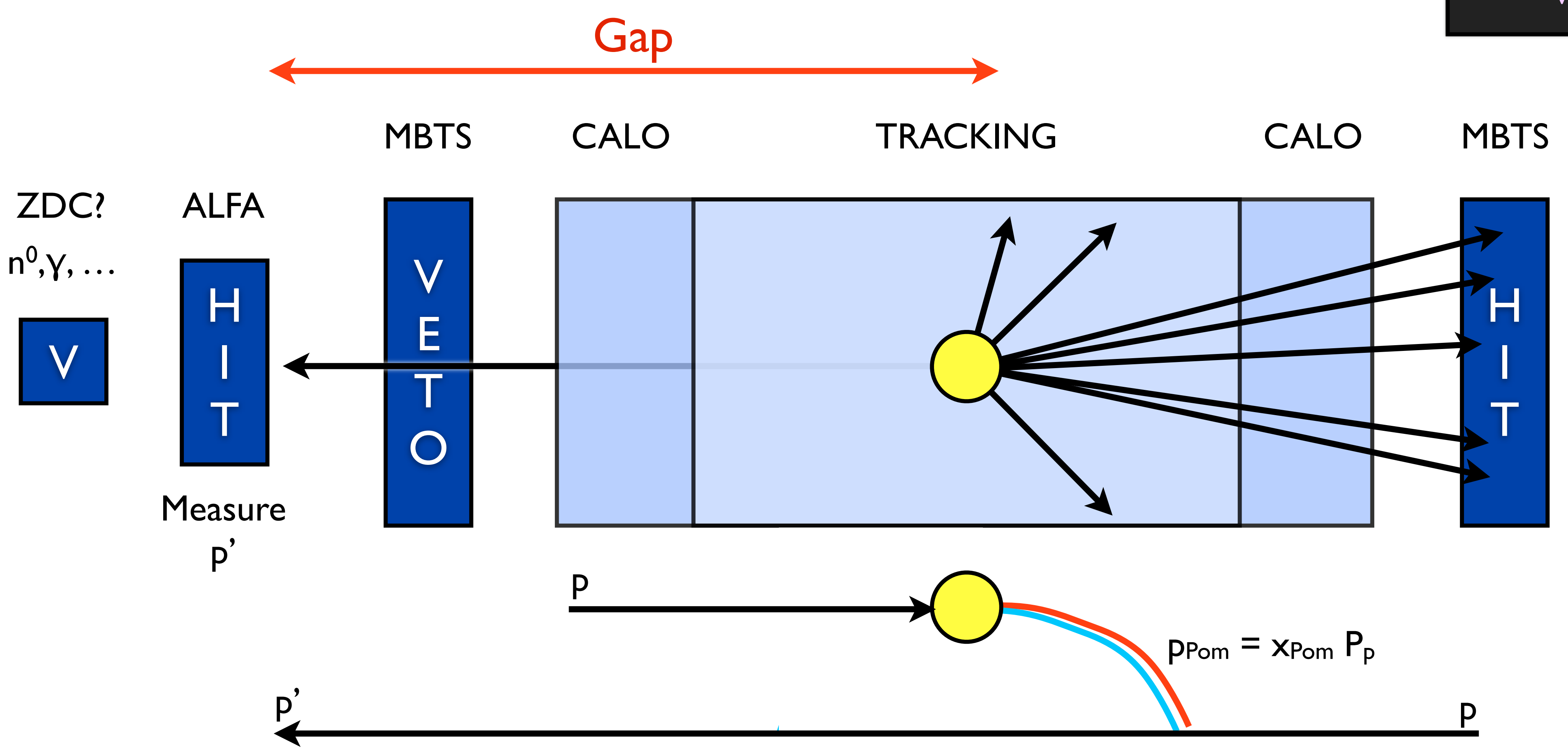

SD: Identified Particles

* Λ and K_S
* Other identified particles?
* Compare to minimum bias

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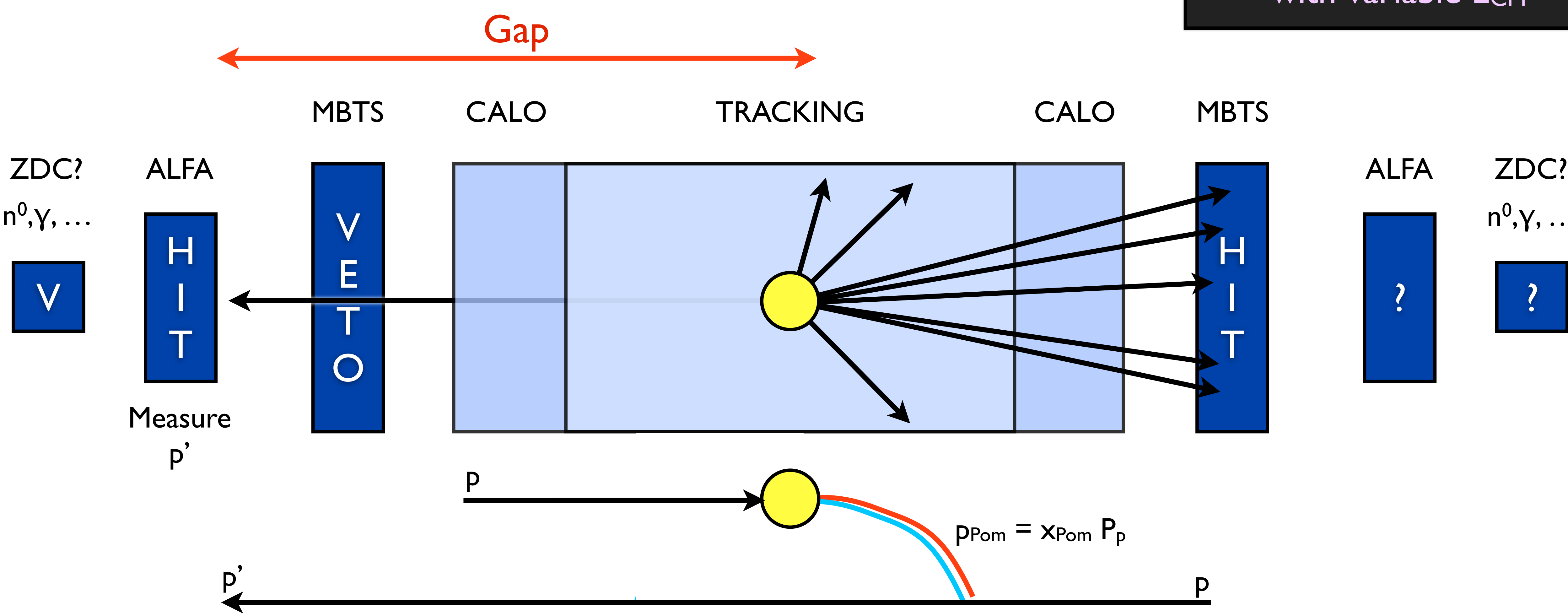

SD DIJETS

* Mass Spectrum (how high can you go?)
* Underlying Event in SD DIJET events
* Dijet Decorrelation $\Delta\varphi_{jj}$
* SD FOUR JETS (MPI in diffraction!)

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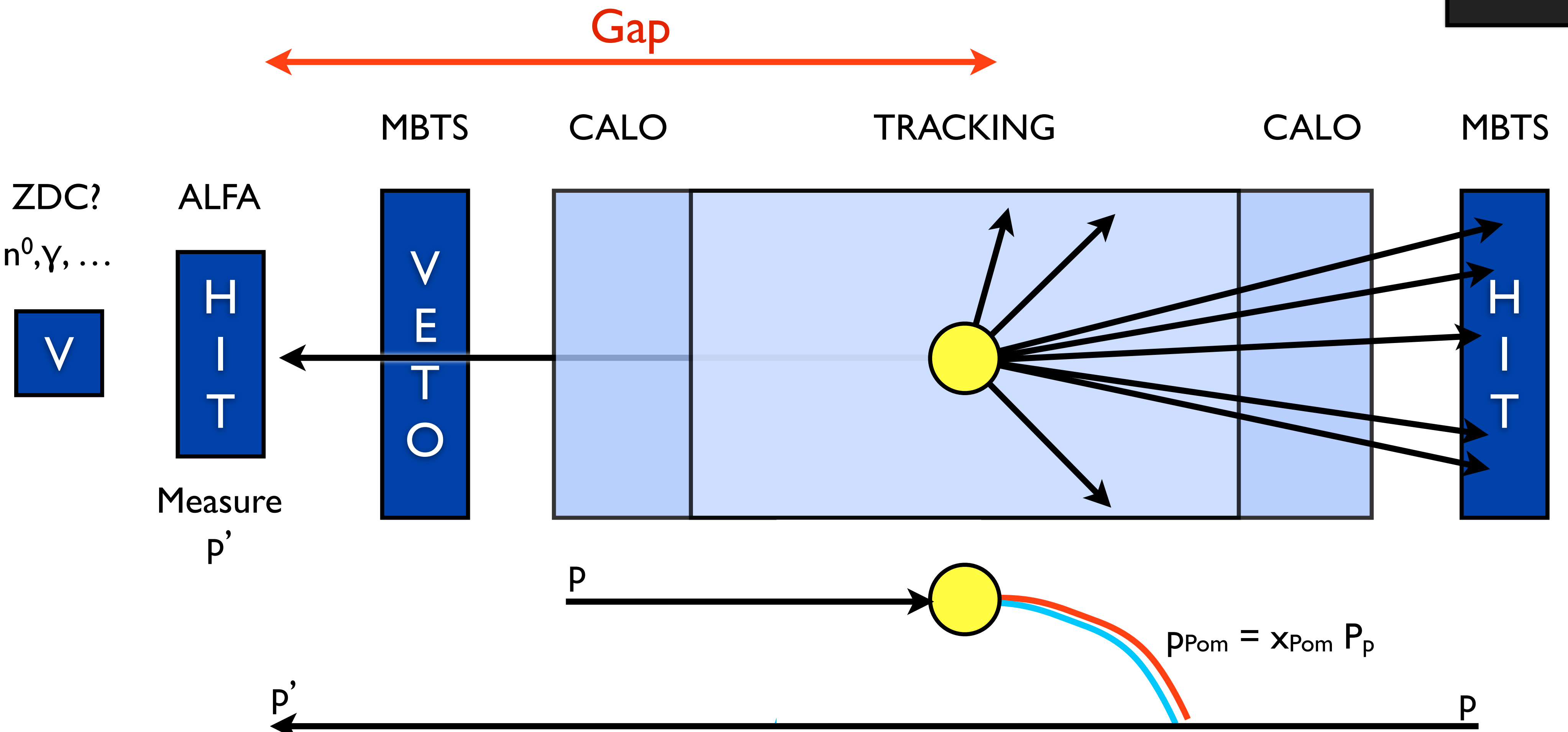

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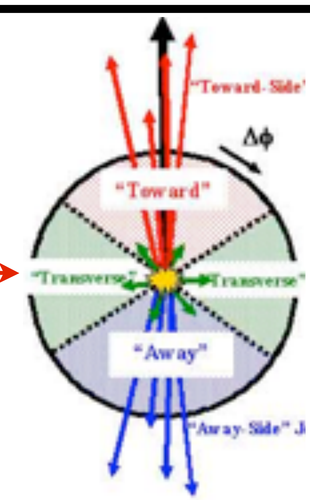

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Central Diffraction

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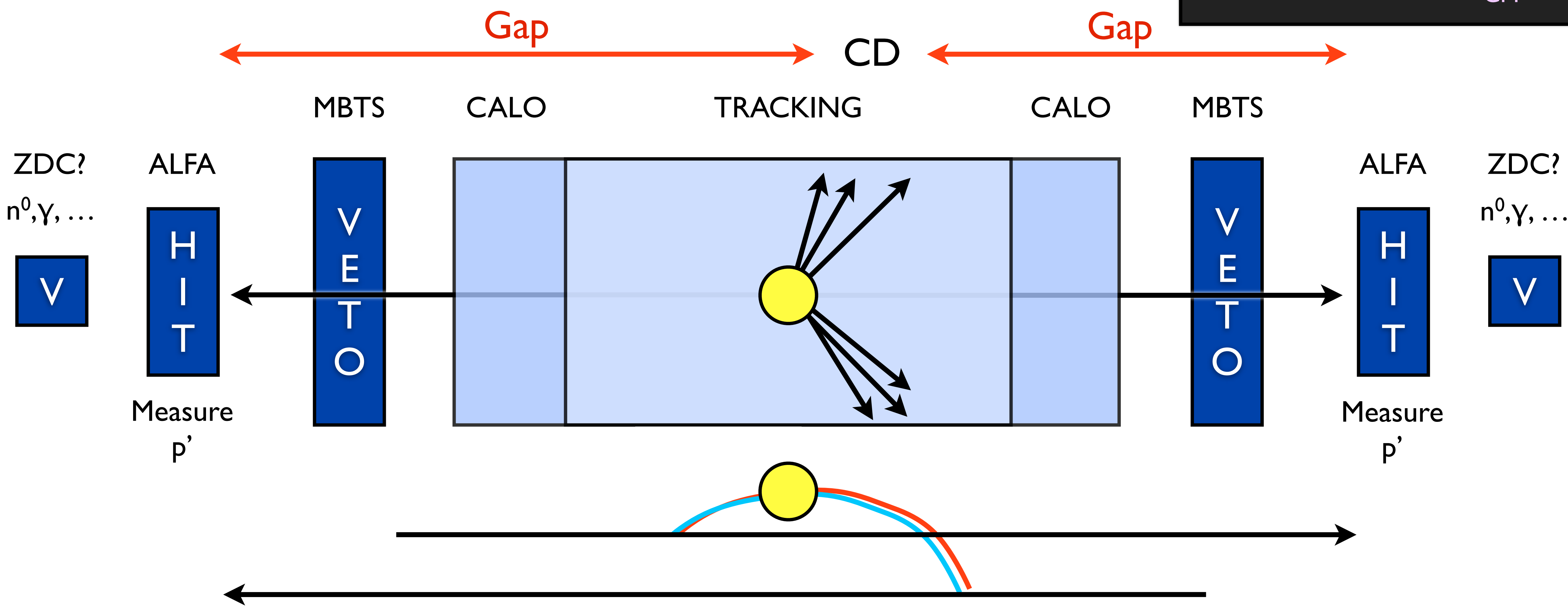

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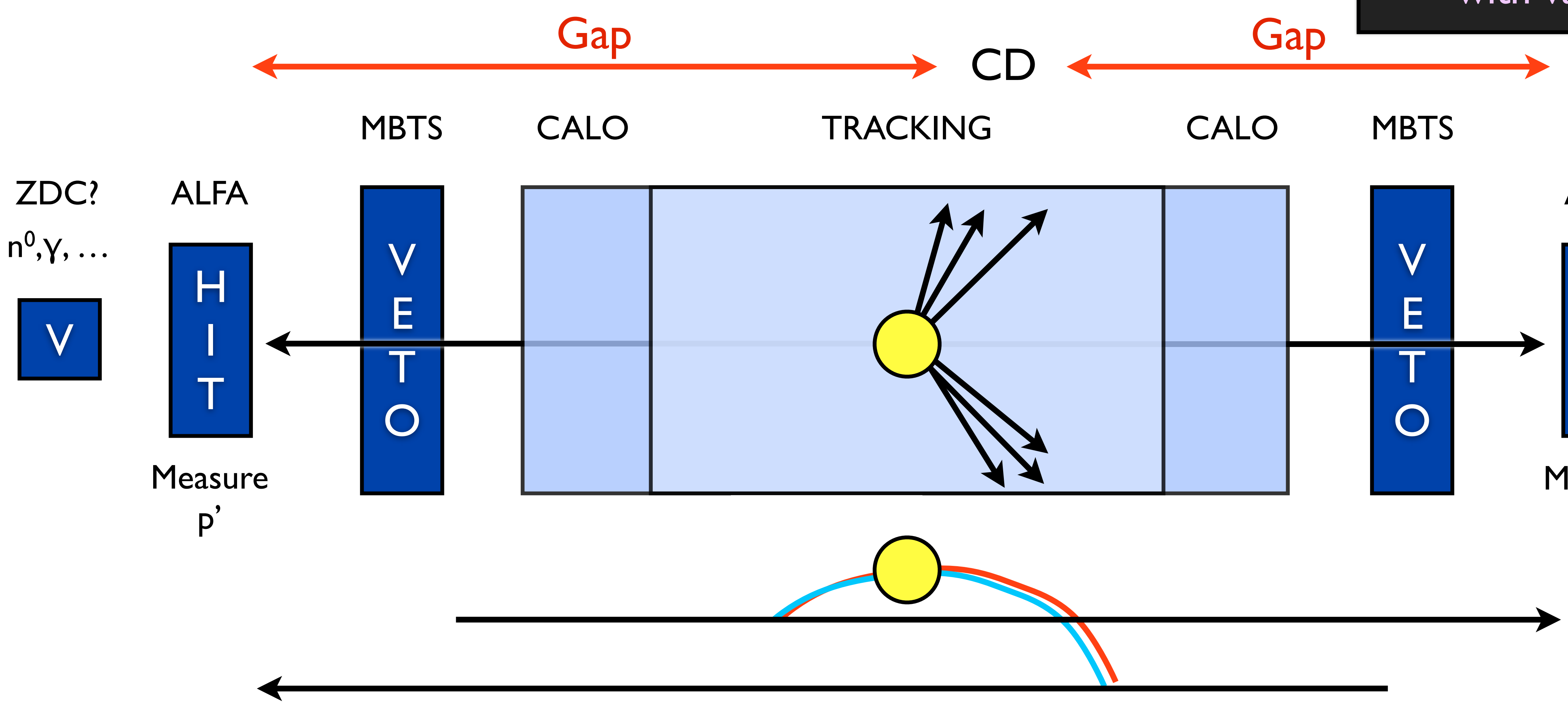


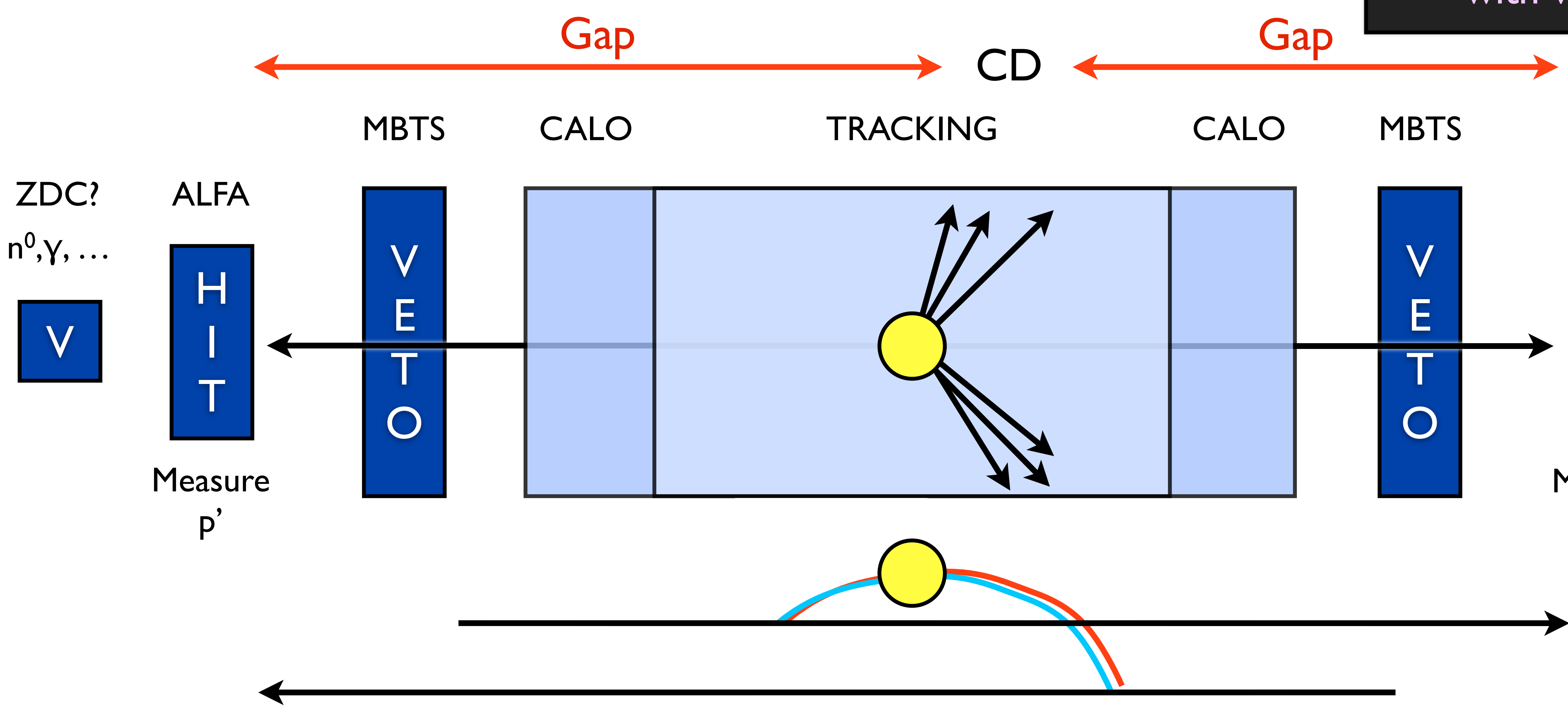
CD

* Mass Spectrum (how high can you go?)
* $\text{Mass}^2 = x_{Pom1}\, x_{Pom2}\, s$
* Rapidity of system → x_{Pom1} / x_{Pom2}

(Some) Opportunities with ALFA + ATLAS

Central Diffraction

Glueball-Glueball Collider with variable E_{CM}



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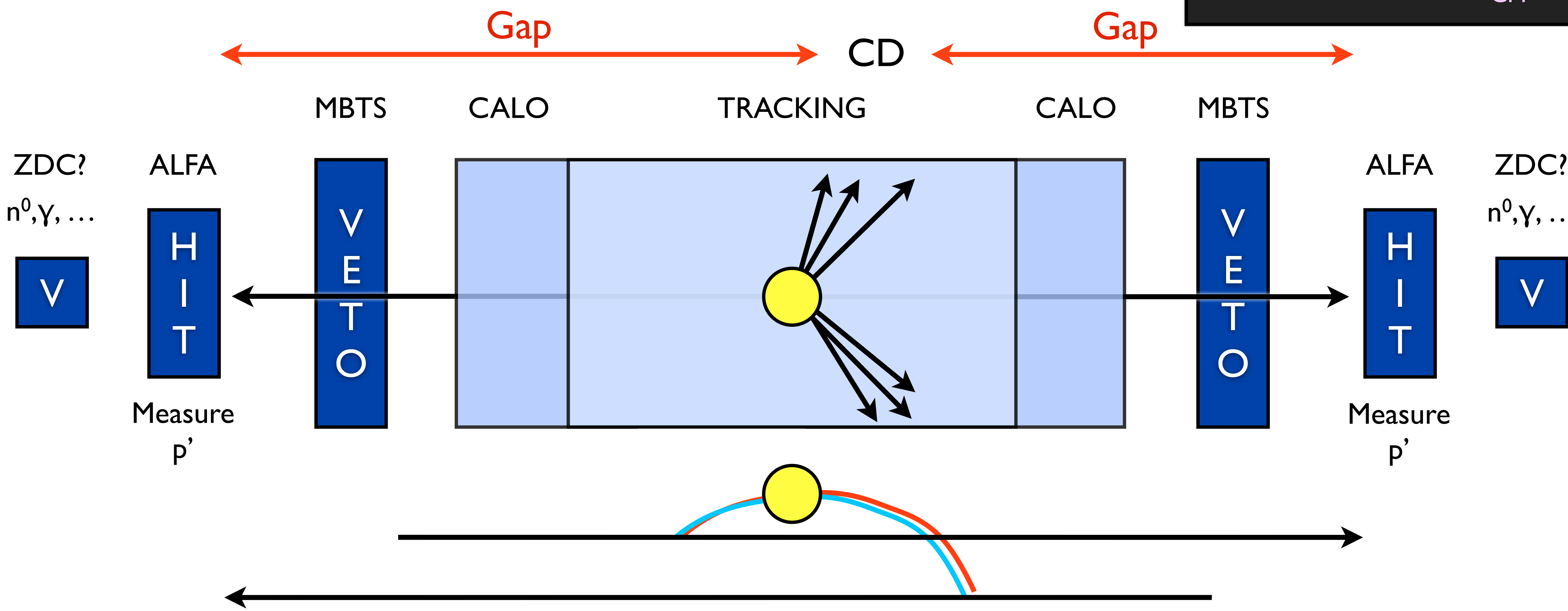

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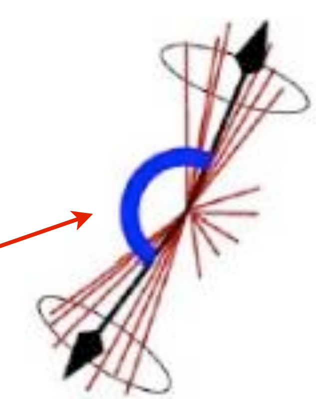
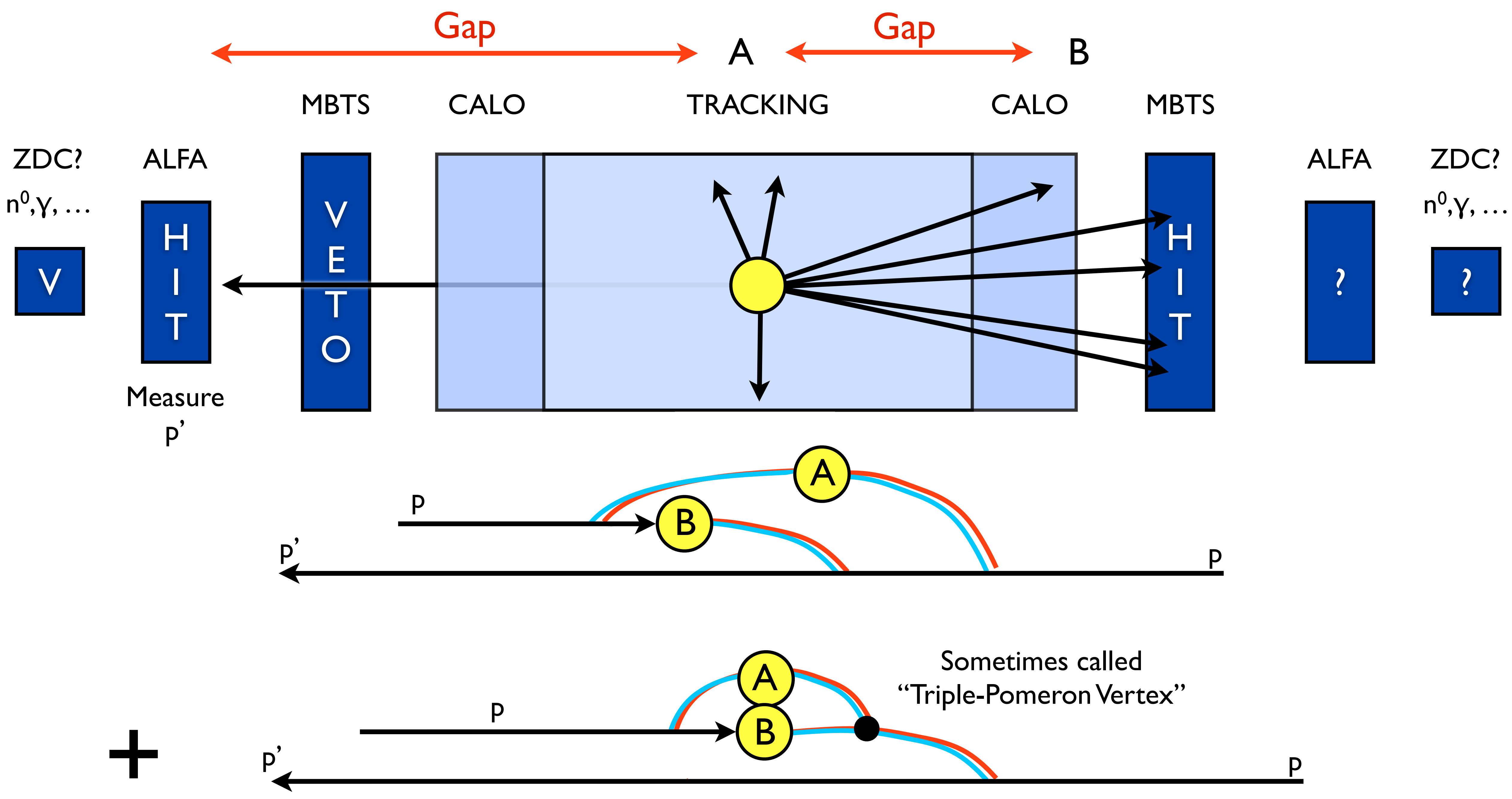


Multi-Gap Diffraction (= Subset of Single-Gap)



Summary

Monte Carlo Event Generators

Aim to describe complete event structure

The MPI that produce the underlying event (UE) in the **central** region also disturb the beam remnant in the **forward** region

→ correlations between central and fwd fragmentation

Current MC constraints sum inclusively over FWD region → blind spot

If there are **big elephants** there, the central constraints would need to be thoroughly re-evaluated

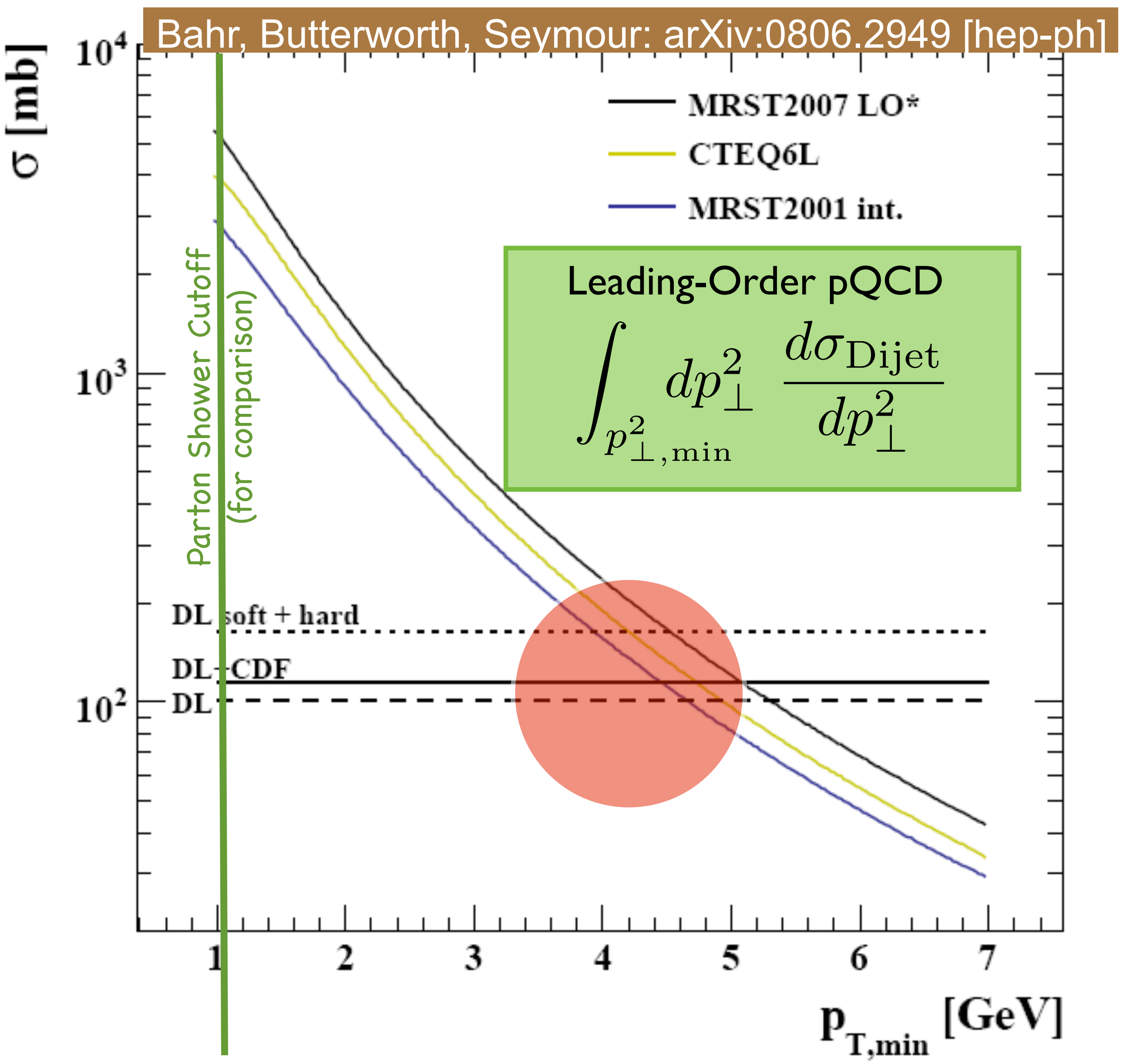
Diffraction

Is not a big elephant for the UE or central physics program (mainly non-diff)

But important for fwd physics + all MCs in active development *(Hard + Central diffraction model in Pythia 8, POMWIG-type model in Herwig++, KMR model in Sherpa)* → need good constraints: → study both diff-enhanced and diff-suppressed triggered samples

Multiple Interactions

= Allow several parton-parton interactions per hadron-hadron collision. Requires extended factorization ansatz.



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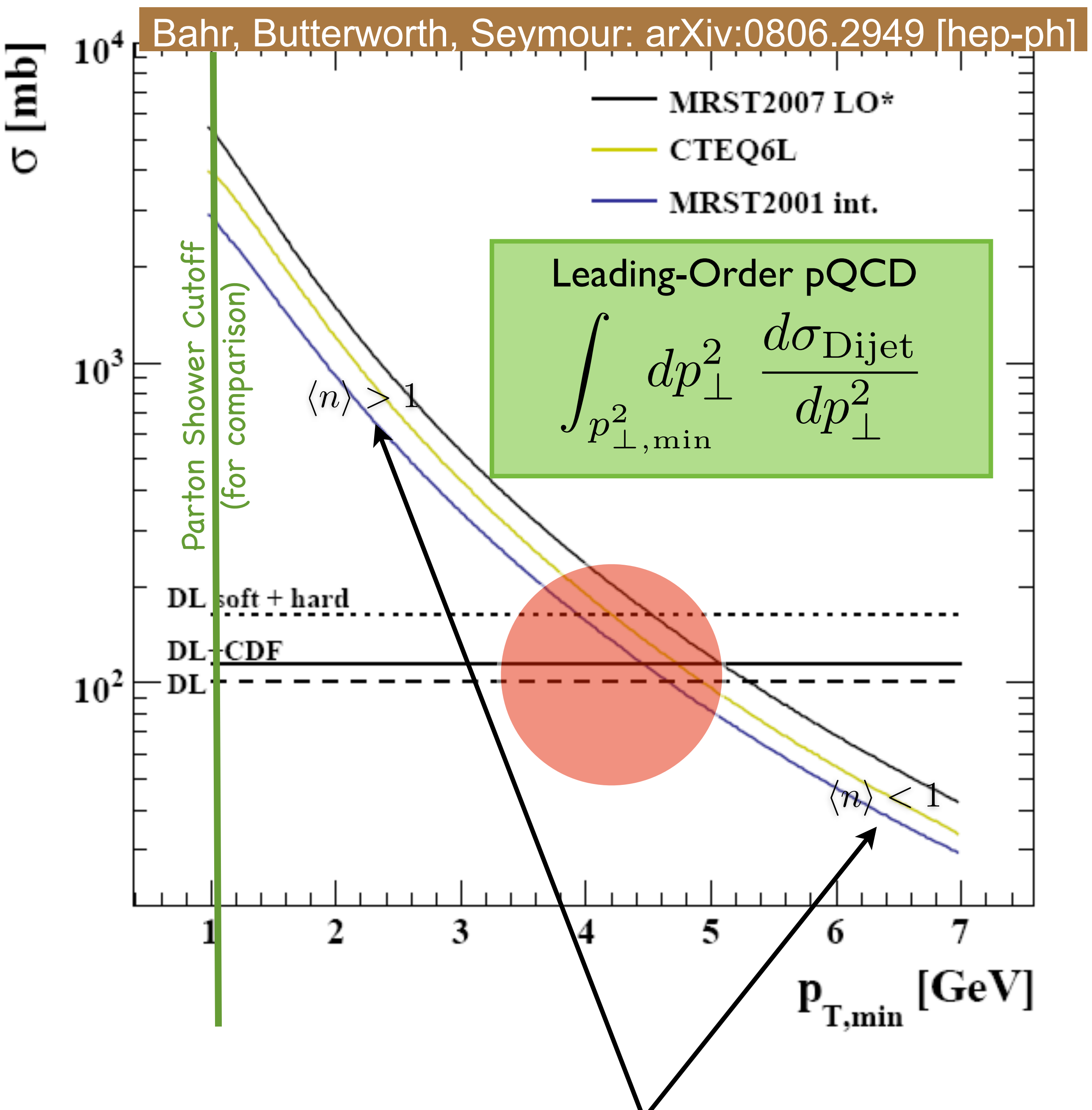

$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\rm tot}$$

Parton-Parton Cross Section

Hadron-Hadron Cross Section

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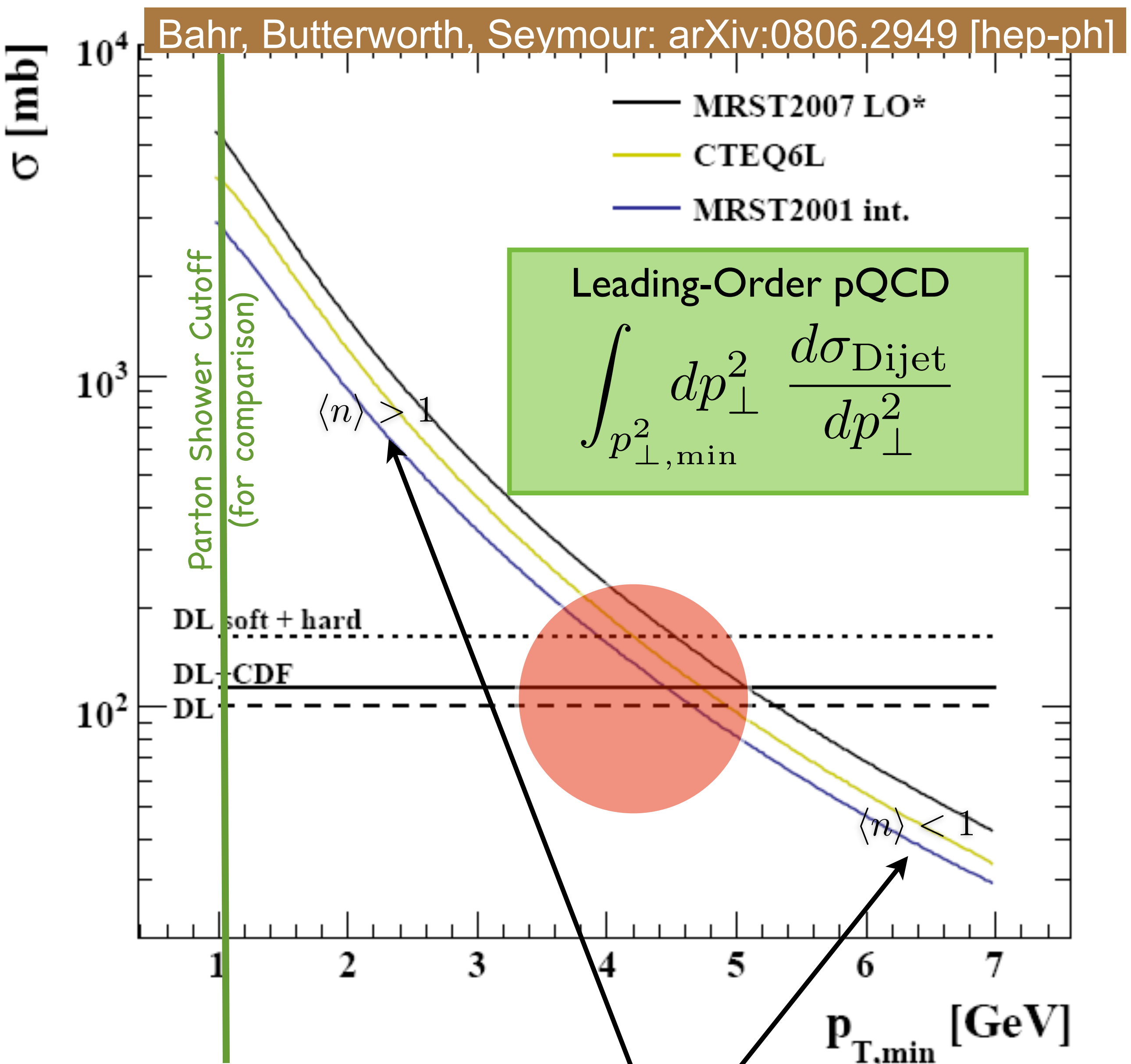
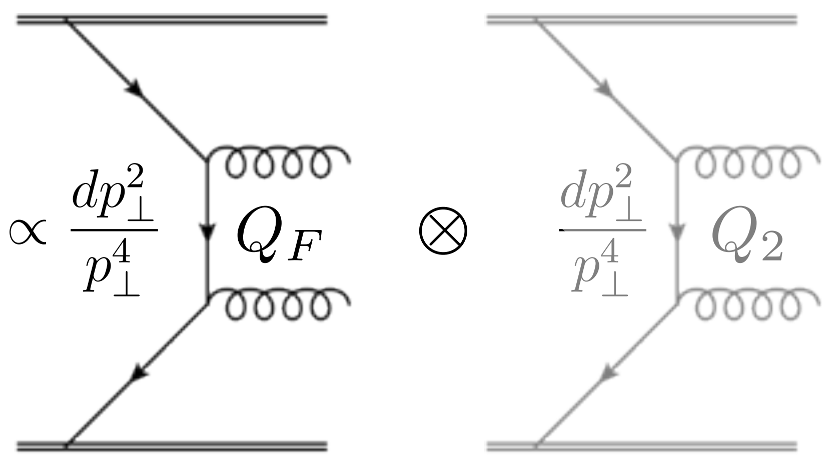


Leading-Order pQCD

$$\int_{p^2_{\perp,\min}} dp^2_\perp \frac{d\sigma_{\rm Dijet}}{dp^2_\perp}$$

Earliest MC model ("old" PYTHIA 6 model)
Sjöstrand, van Zijl PRD36 (1987) 2019



$$d\sigma_{2\to2} \propto \frac{dp^2_\perp}{p^4_\perp} \; Q_F \; \otimes \; \frac{dp^2_\perp}{p^4_\perp} \; Q_2 \; \cdots$$

Lesson from bremsstrahlung in pQCD: divergences → fixed-order breaks down
Perturbation theory still ok, with resummation (unitarity)

→ Resum dijets?
Yes → MPI!

$$\sigma_{2\to2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min}) \; \sigma_{\rm tot}$$

Parton-Parton Cross Section

Hadron-Hadron Cross Section

How many?

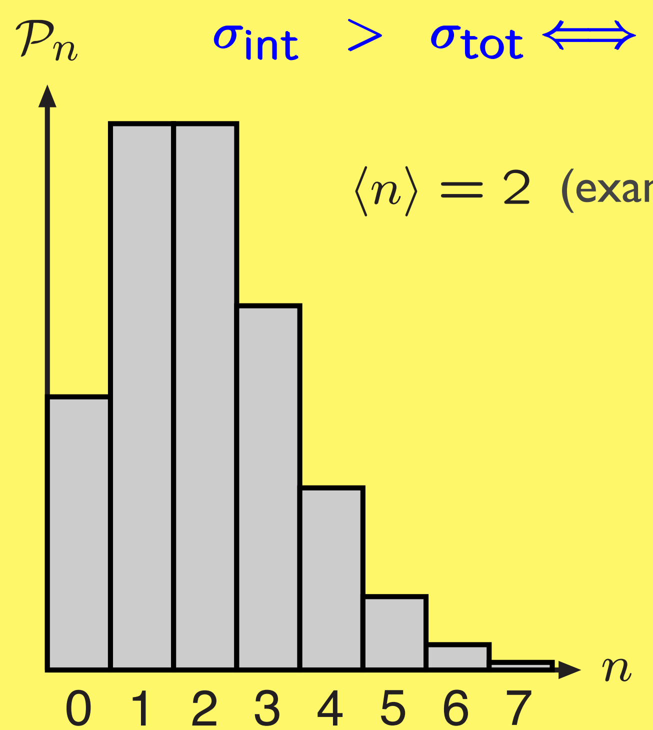
Naively $\langle n_{2\to2}(p_{\perp\min})\rangle = \dfrac{\sigma_{2\to2}(p_{\perp\min})}{\sigma_{\text{tot}}}$

Interactions independent (naive factorization) → Poisson

$$\sigma_{\text{tot}} = \sum_{n=0}^{\infty} \sigma_n$$

$$\sigma_{\text{int}} = \sum_{n=0}^{\infty} n\,\sigma_n$$

$$\sigma_{\text{int}} > \sigma_{\text{tot}} \Longleftrightarrow \langle n\rangle > 1$$



$$\mathcal{P}_n = \frac{\langle n\rangle^n}{n!}\, e^{-\langle n\rangle}$$

How many?

Naively $\langle n_{2\to2}(p_{\perp\min})\rangle = \frac{\sigma_{2\to2}(p_{\perp\min})}{\sigma_{\mathrm{tot}}}$

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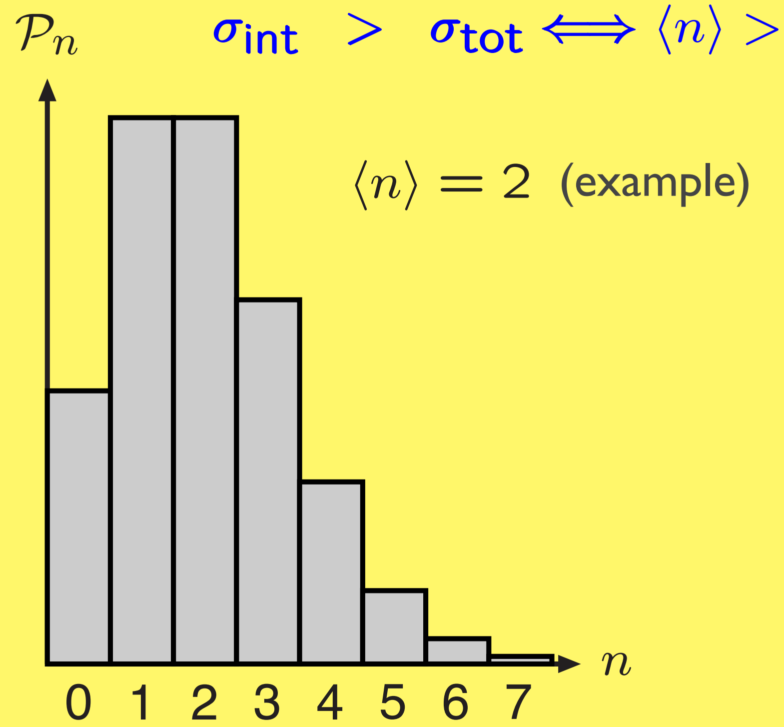


$$\mathcal{P}_n = \frac{\langle n\rangle^n}{n!} e^{-\langle n\rangle}$$

Real Life

Momentum conservation suppresses high-n tail

+ physical correlations → not simple product

1: A Simple Model

The minimal model incorporating single-parton factorization, perturbative unitarity, and energy-and-momentum conservation

$$\sigma_{2\to 2}(p_{\perp\min}) = \langle n \rangle (p_{\perp\min})\ \sigma_{\mathrm{tot}}$$

Parton-Parton Cross Section — Hadron-Hadron Cross Section

1. Choose $p_{T\min}$ cutoff
   = main tuning parameter

2. Interpret $<n>(p_{T\min})$ as mean of Poisson distribution
   Equivalent to assuming all parton-parton interactions equivalent and independent ~ each take an instantaneous "snapshot" of the proton

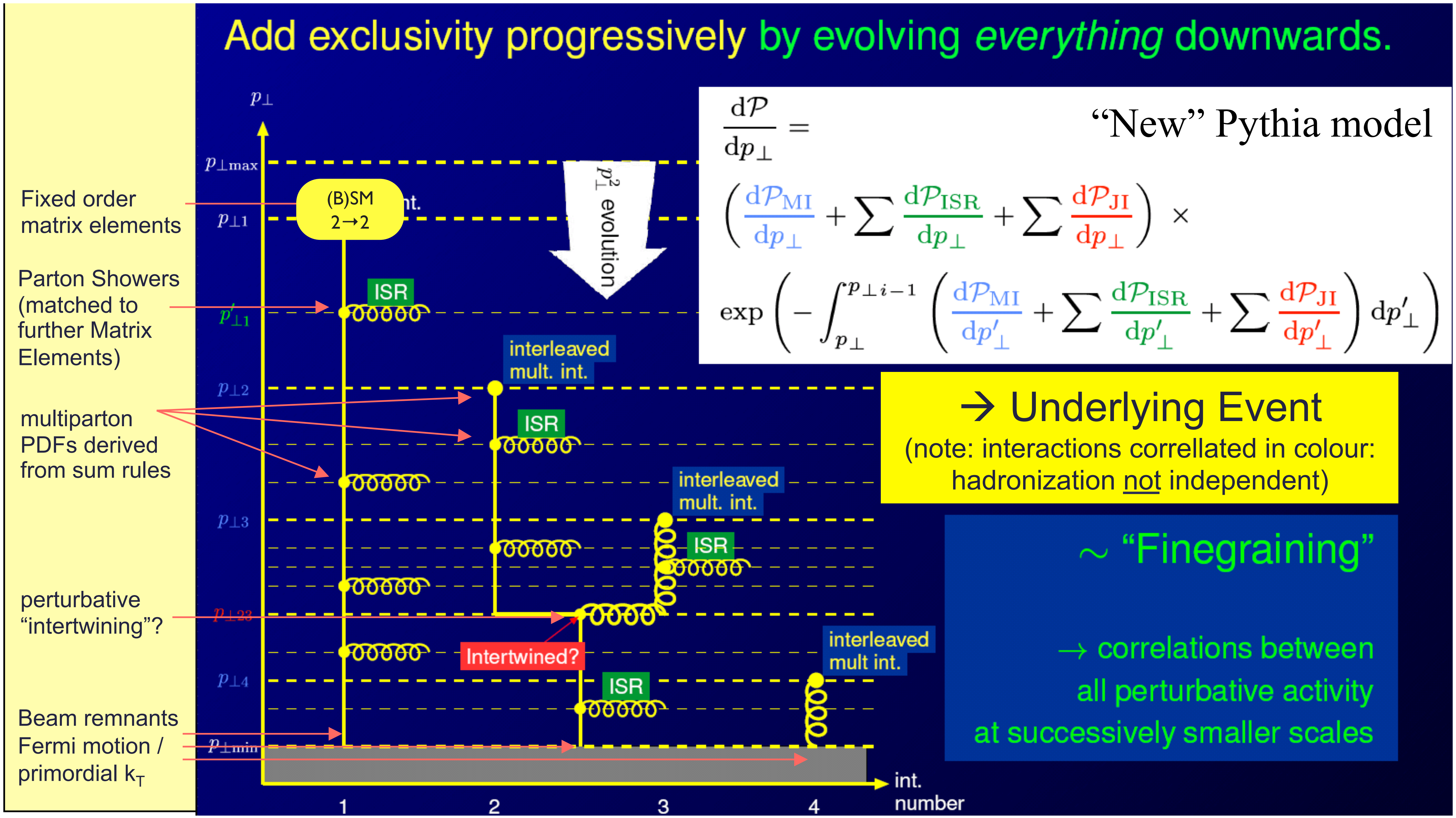
3. Generate n parton-parton interactions (pQCD 2→2)
   Veto if total beam momentum exceeded → overall (E,p) cons

4. Add impact-parameter dependence → $<n> = <n>(b)$
   Assume factorization of transverse and longitudinal d.o.f., → PDFs : $f(x,b) = f(x)g(b)$ (Ordinary CTEQ, MSTW, NNPDF, … ↓ $f(x)$)
   b distribution ∝ EM form factor → **JIMMY model** Butterworth, Forshaw, Seymour Z.Phys. C72 (1996) 637
   Constant of proportionality = second main tuning parameter

5. Add separate class of "soft" (zero-p_T) interactions representing interactions with $p_T < p_{T\min}$ and require $\sigma_{\mathrm{soft}} + \sigma_{\mathrm{hard}} = \sigma_{\mathrm{tot}}$
   → **Herwig++ model** Bähr et al, arXiv:0905.4671

2: Interleaved Evolution

Sjöstrand & Skands, JHEP 0403 (2004) 053; EPJ C39 (2005) 129



Also available for Pomeron-Proton collisions since Pythia 8.165