小x物理简单介绍和小x event generator

Jian Zhou

山东大学(青岛)
SHANDONG UNIVERSITY, QINGDAO

In collaboration with Wei yao Ke, Xu Liu, Yu Shi, Xin nian Wang

The first small-x Workshop at the LHC in China, Wuhan, CCNU, 2026.07.06-09

Outline:

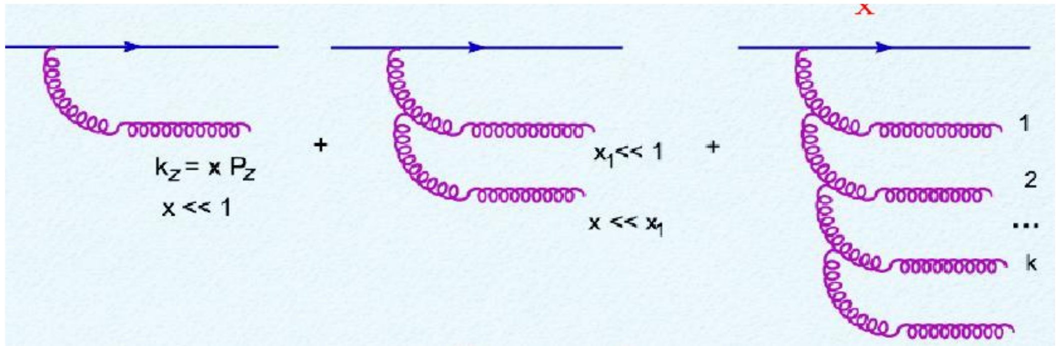
- A pedagogical introduction to small x physics
- Observables sensitive to small x physics
- Small x event generator
- Summary

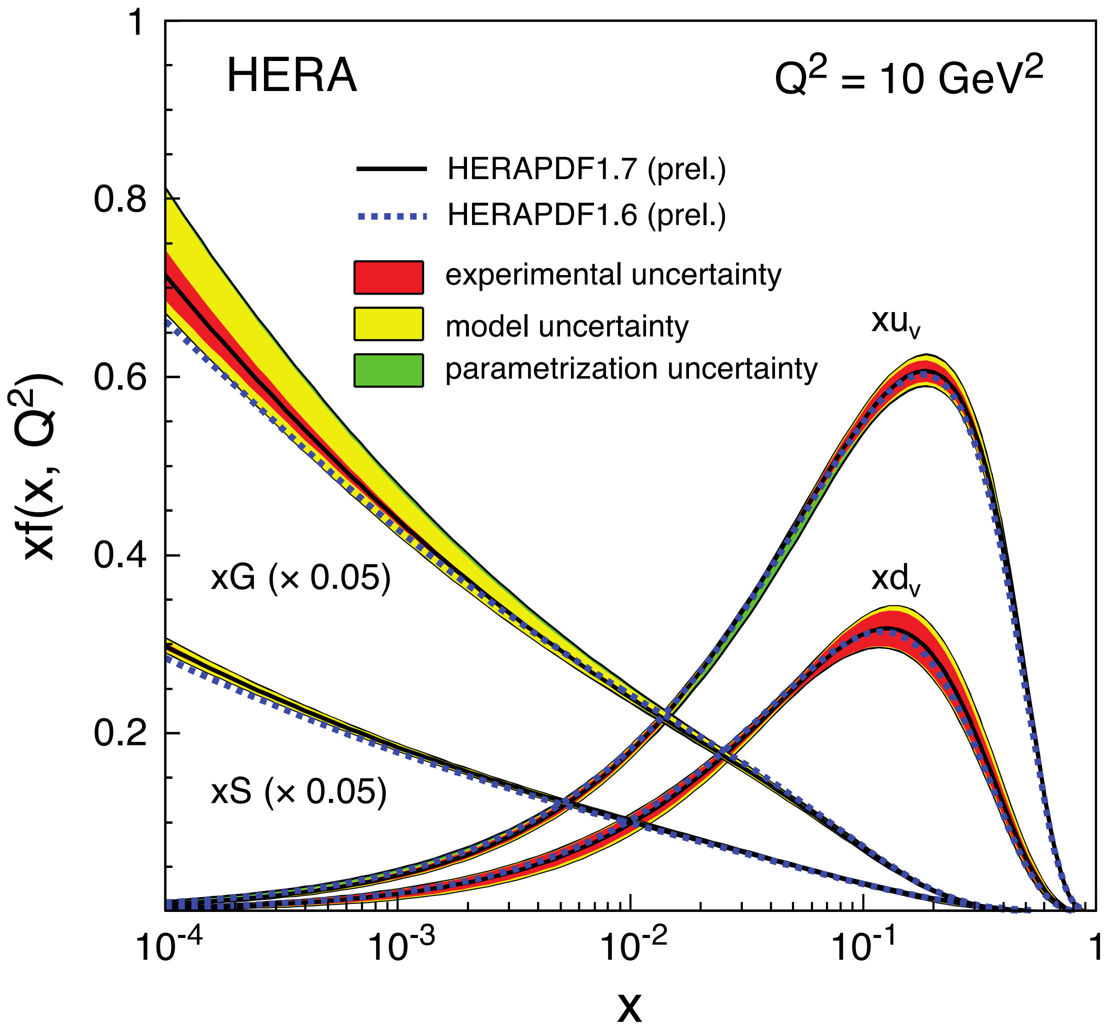
本报告图片由GPT image 2制作

Glouns at small x

DGLAP splitting function

$$P_{gg}(x) \sim \frac{1}{x} \text{ for } x \to 0$$

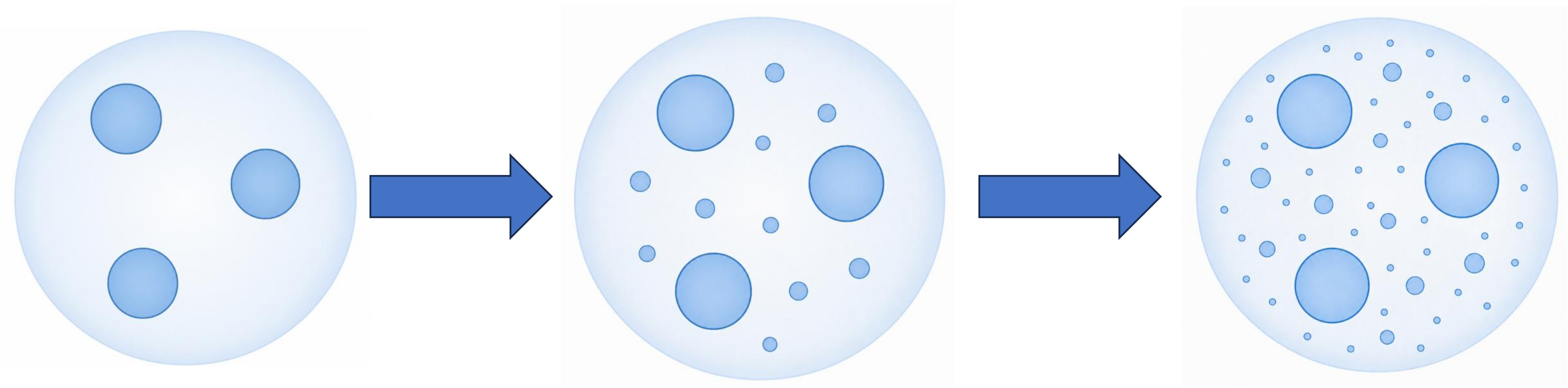




多小的x算小x: x=0.01

Why small x physics interesting?

- **Transverse size of gluon is reversely proportional to its kt**
- **First partons are produced with relatively large size(small kt).**
- **When some critical density is reached no more partons of given size can fit in the wave function. Smaller gluon(larger kt) is produced to fit the rest space.**
- **Average kt increase with increasing number density.**



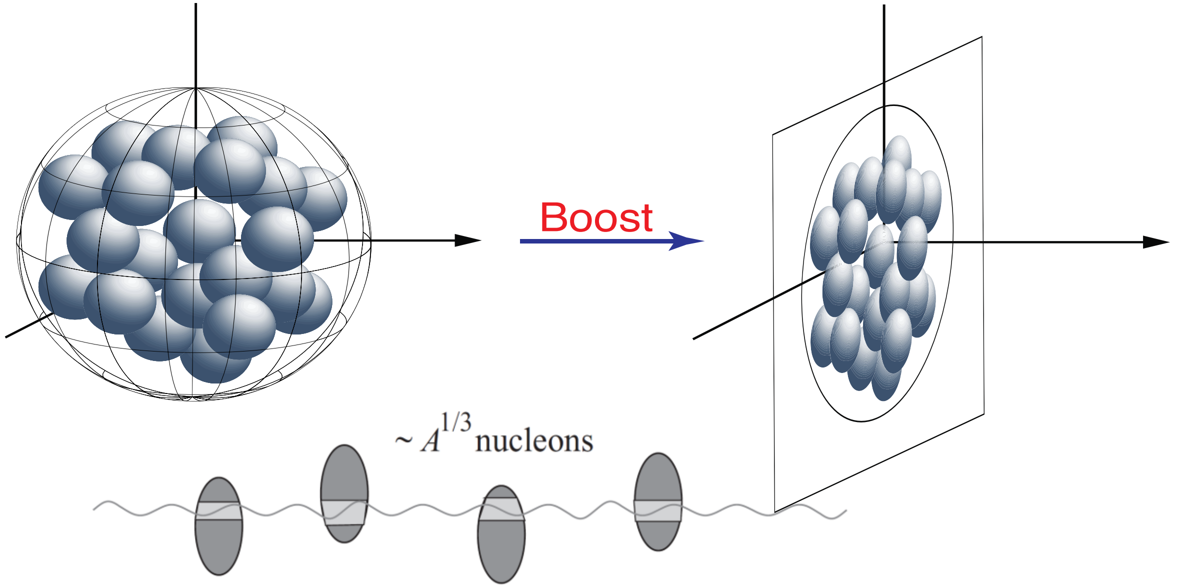
Perturbative calculable!

Why do we need a nucleus target

◆ A semi-hard scale Qs emerge when gluon density is very high

Q_s^2 ∞ gluons per unit transverse area

□ To reach high gluon density: very small x & large nucleus



Small x gluons(with long wave length) from different nucleons overlap with each other!

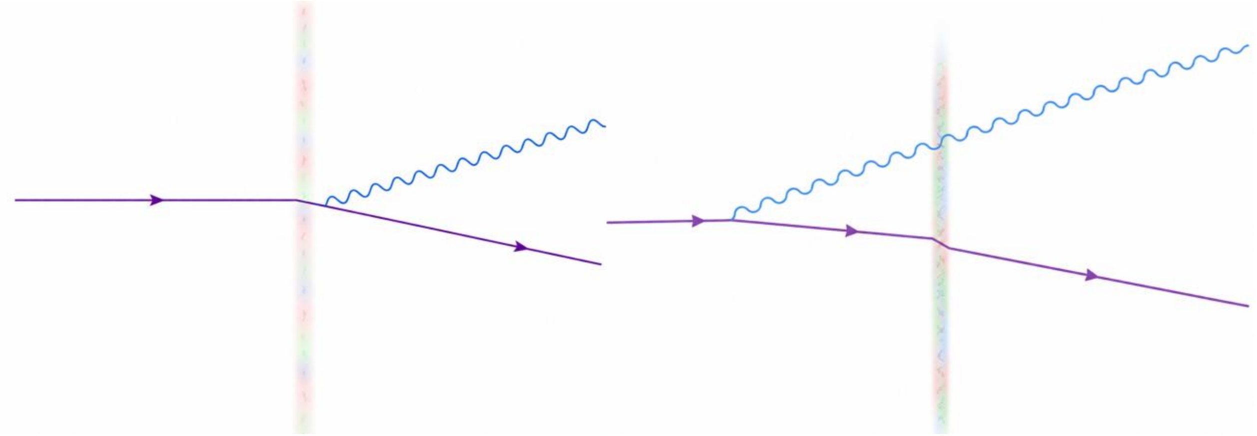
$$Q_s^2(x) \sim \left(\frac{A}{x}\right)^{1/3}$$

rcBK

质子: x=0.00001
金核: x=0.01

How to probe gluon distribution

Dipole gluon TMD：



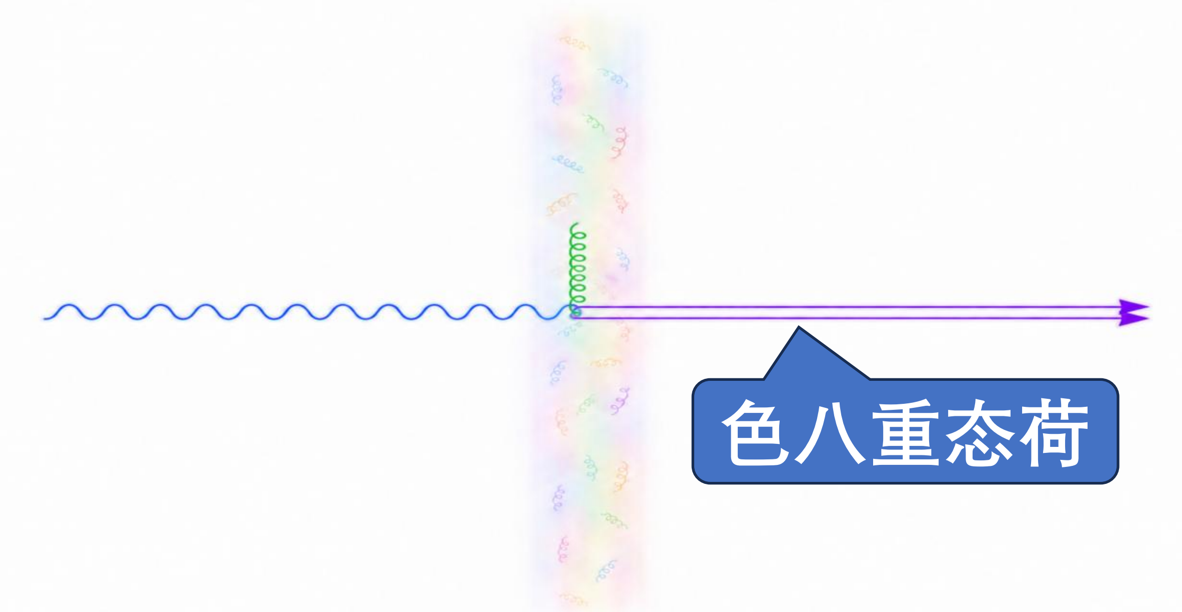
初态多重散射

末态多重散射

Low qt: q_t^2

high qt: $1/q_t^2$

WW gluon TMD：



多重散射

Low qt: $\ln(Q_s^2/q_t^2)$

high qt: $1/q_t^2$

F. Dominguez, B-W. Xiao, F. Yuan 2011
F. Dominguez, C. Marquet, B-W. Xiao, F. Yuan 2011

Background II

MV model: Classical gluon fields:

- For $Q_s >> \Lambda_{QCD}$, $\alpha_s(Q_s^2) \ll 1$

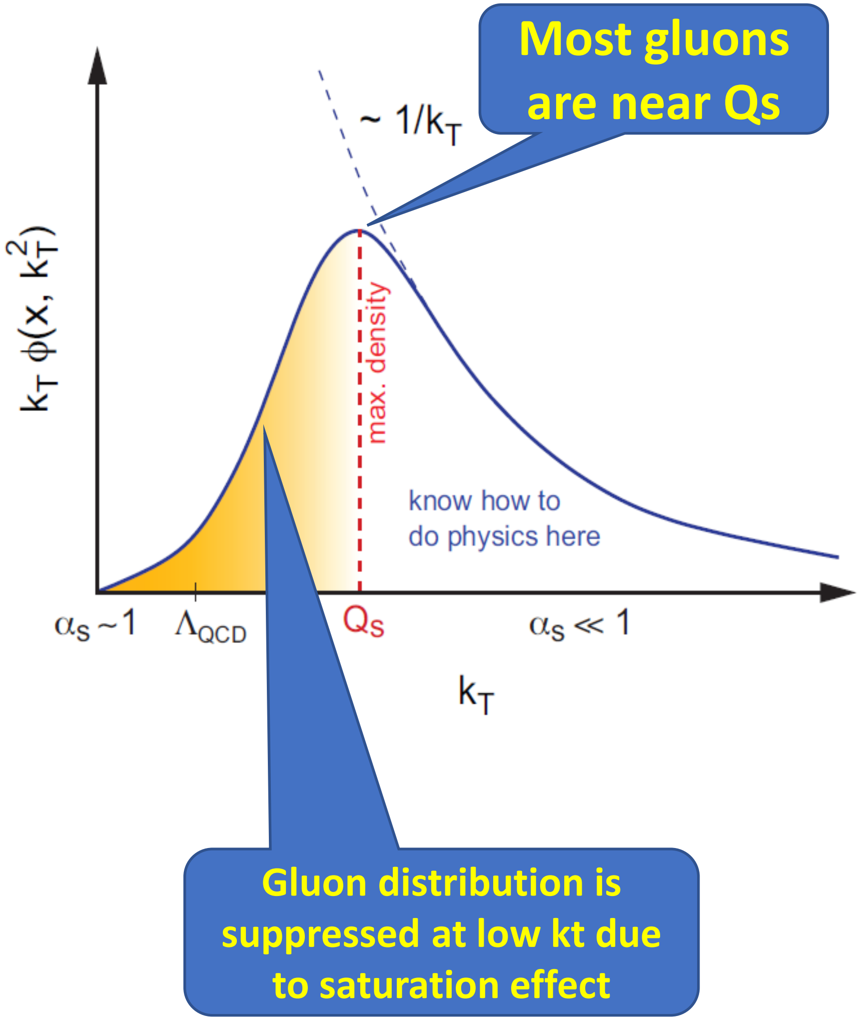
Perturbative treatment is justified!

- In the small x limit, high occupation number

A semi-classical treatment is justified

MV model & Glauble-Mueller model applied at x=0.01

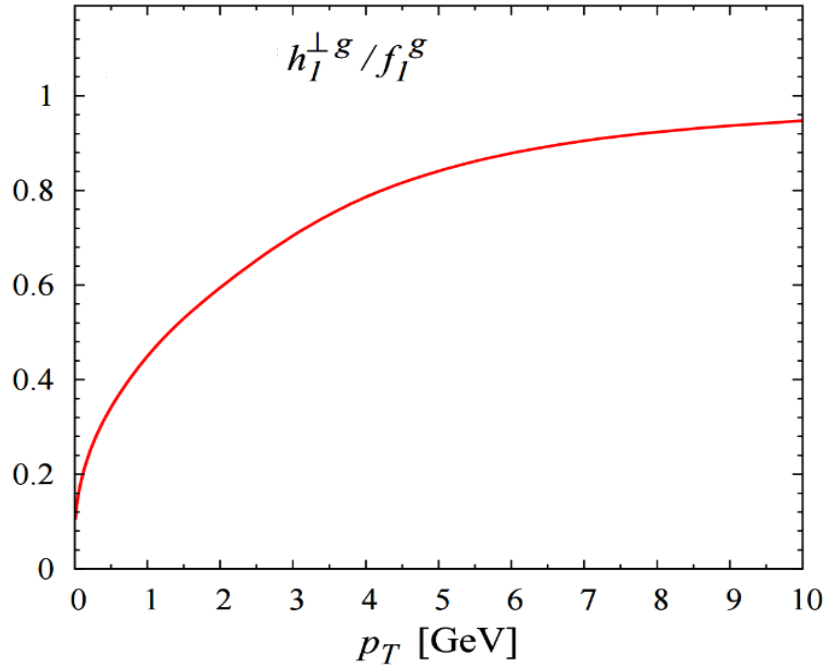
Dipole distribution amplitude



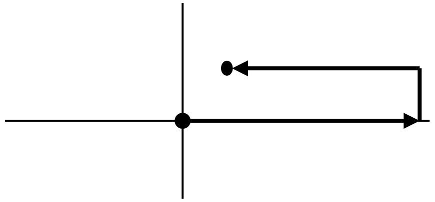
Gluon TMDs in the MV model

- The linearly polarized gluon TMDs in the MV model,

Metz & ZJ, 2011

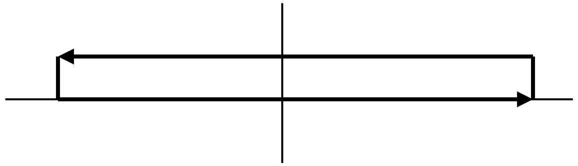


Weizsäcker-Williams(WW) distribution:



$$xh_{1,WW}^{\perp g}(x,k_\perp) = \frac{N_c^2-1}{8\pi^3} S_\perp \int d\xi_\perp \frac{K_2(k_\perp \xi_\perp)}{\frac{1}{4\mu_A}\xi_\perp Q_s^2}\left(1-e^{-\frac{\xi_\perp^2 Q_s^2}{4}}\right)$$

Dipole distribution:



$$xh_{1,DP}^{\perp g}(x,k_\perp) = xG_{DP}^g(x,k_\perp) = \frac{k_\perp^2 N_c}{2\pi^2\alpha_s} S_\perp \int \frac{d^2\xi_\perp}{(2\pi)^2} e^{-i\vec{k}_\perp\cdot\vec{\xi}_\perp} e^{-\frac{Q_{sq}^2 \xi_\perp^2}{4}}$$

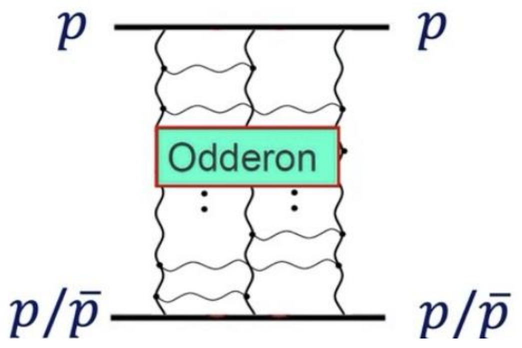
positivity bound saturated for any value of k_t

Odderon and asymmetric color source distribution

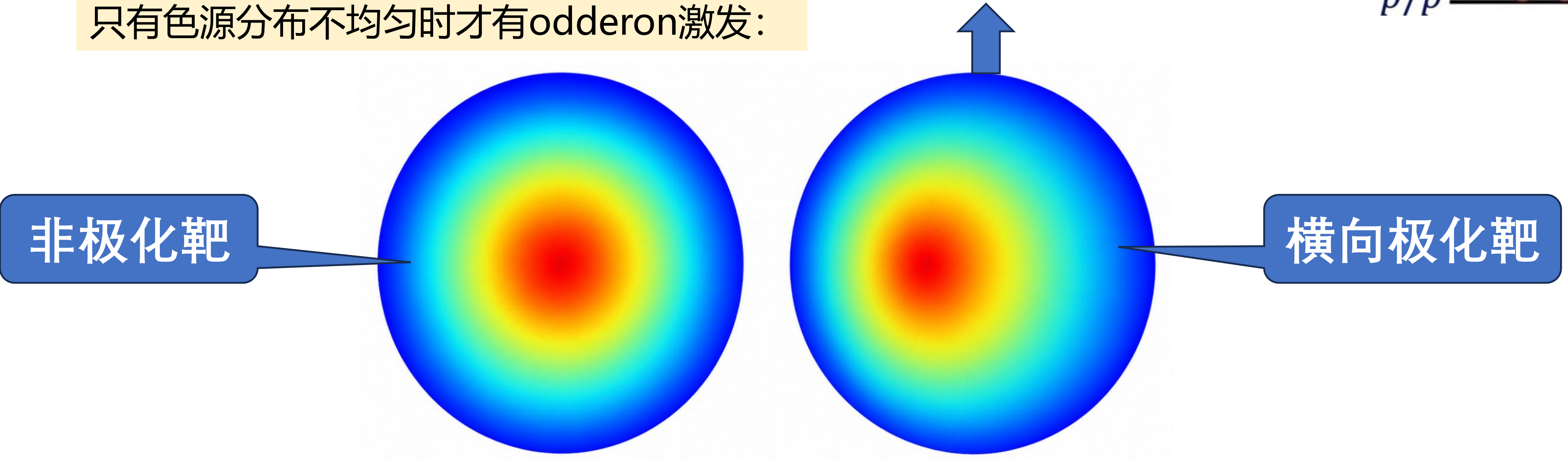
Odderon, a colorless exchange with C=-1

Łukaszuk, L.; Nicolescu, 1973

3胶子交换，色对称态（反色对称态不是odderon)



只有色源分布不均匀时才有odderon激发:



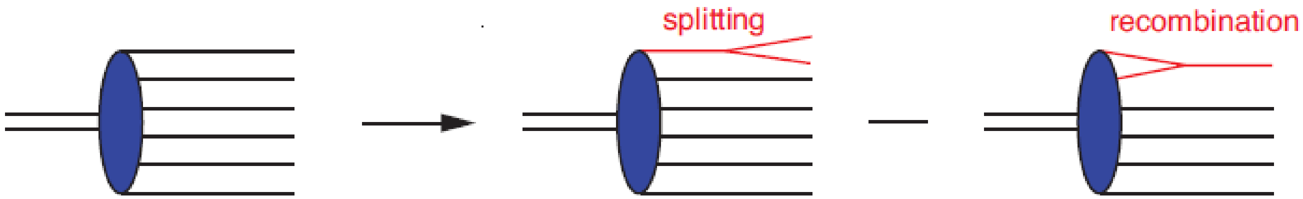
激发odderon

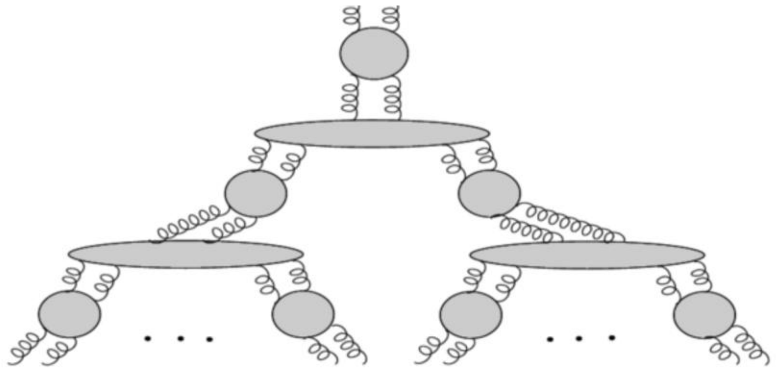
激发spin dependent odderon ZJ 2013

模型计算表明spin dependent odderon 更大

Small x evolution equations

必须要考虑胶子融合/重散射：





- 胶子数密度随x增长行为： $\frac{1}{x^{1+\delta}}$ 量子修正
- 胶子平均横动量随x增长行为： $Q_s^2(x)$

BFKL → GLR/MQ → BK → JIMWLK

线性方程，无胶子融合

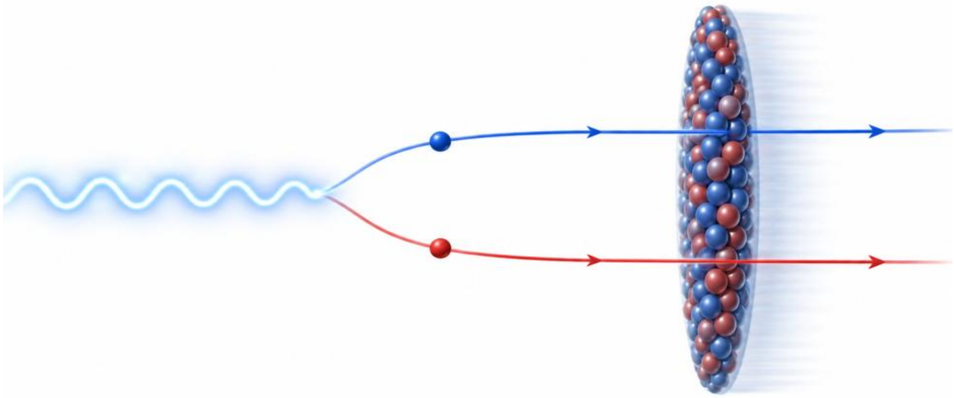
2->1 胶子融合

胶子融合（重散射)求和到无穷阶，large N_C 近似，闭合方程

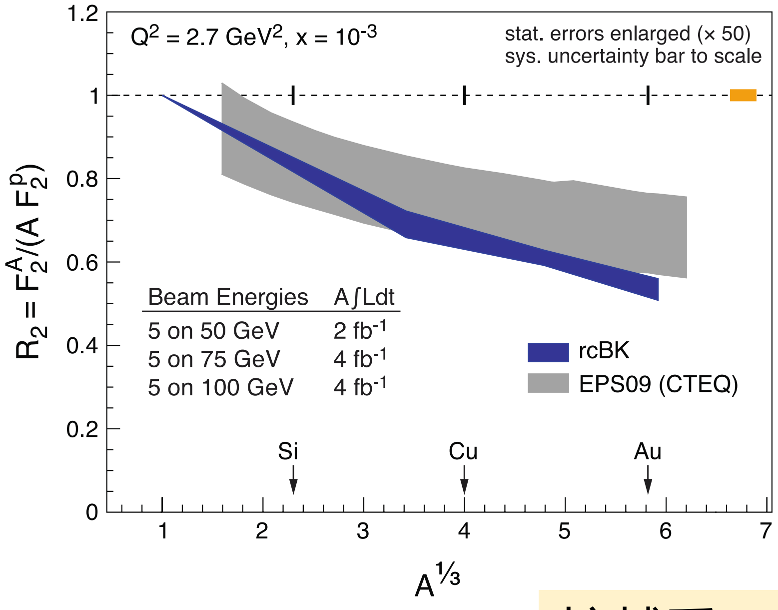
完整的小x演化方程，非闭合

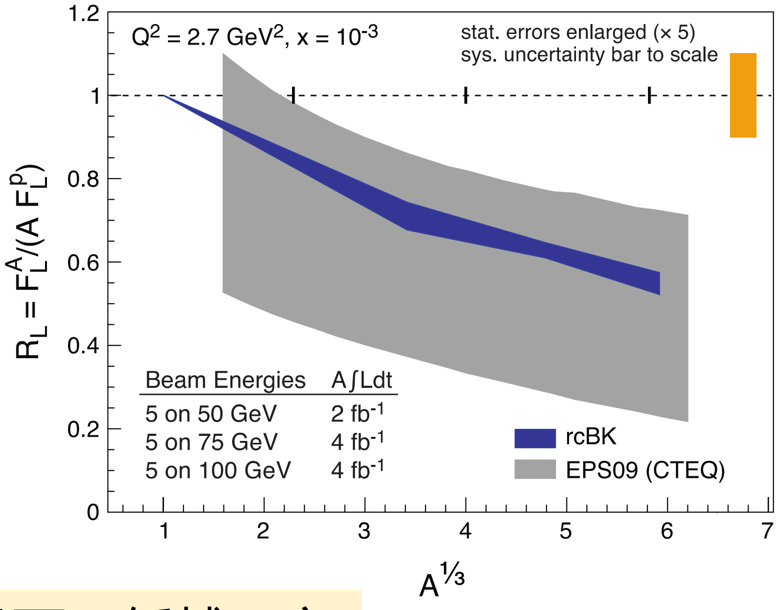
Nuclear suppression

DIS过程的dipole图像：



在相同的运动学区，对比ep, eA inclusive cross section:

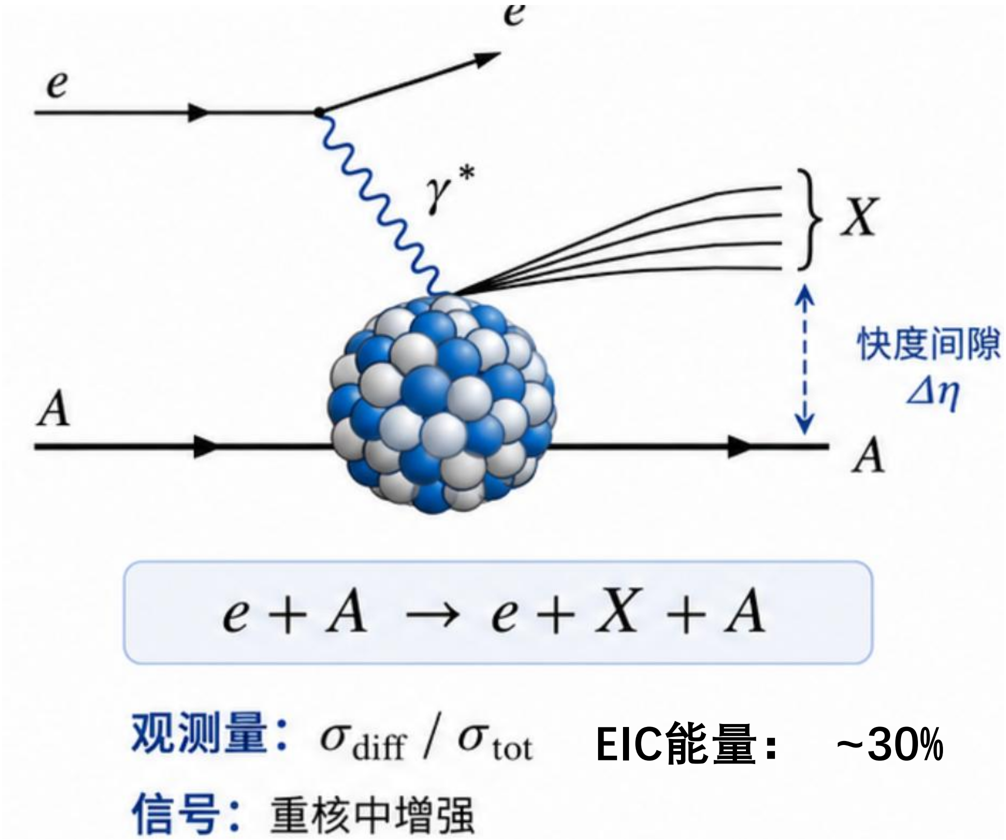




核越重，总截面压低越厉害

Saturation 探针

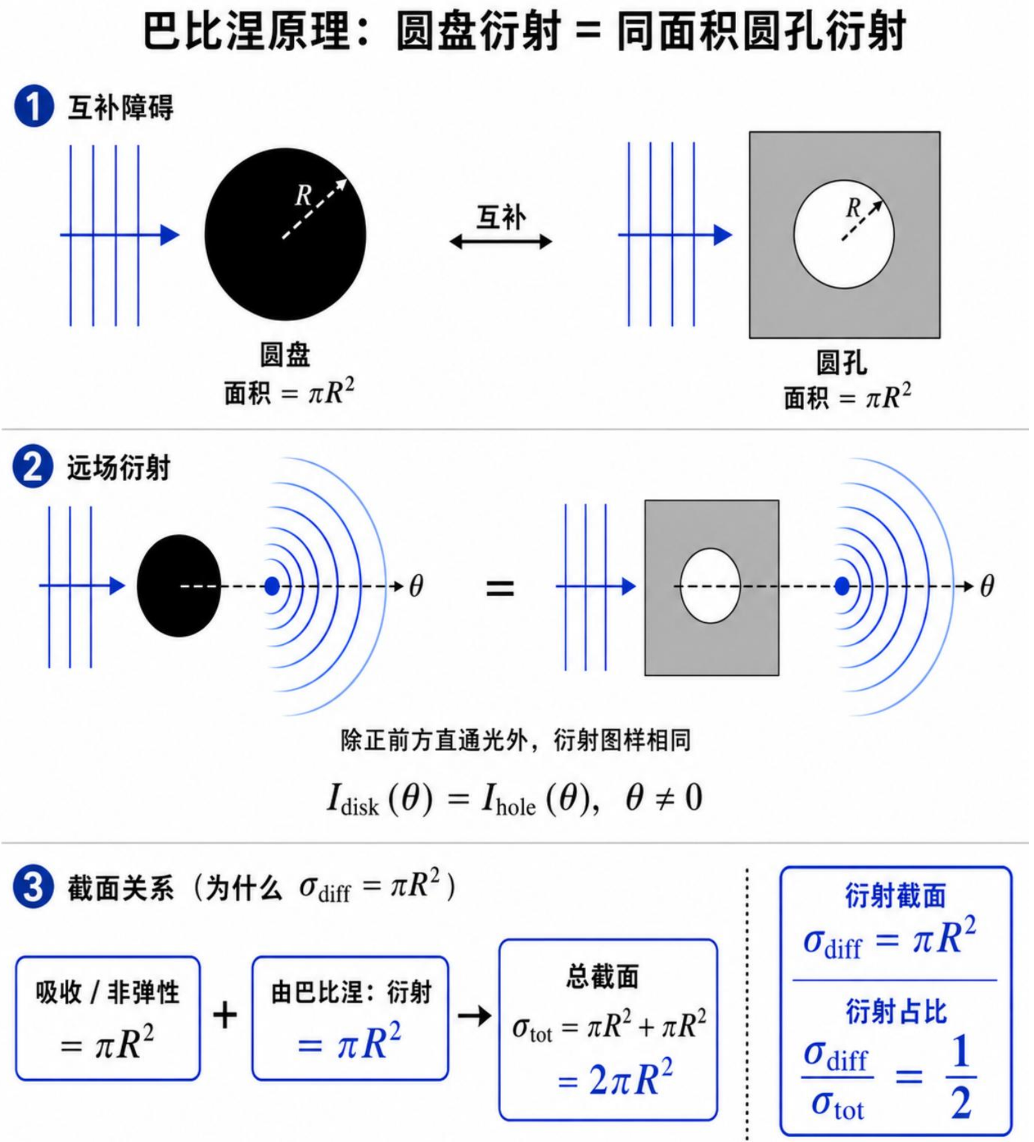
相干衍射：



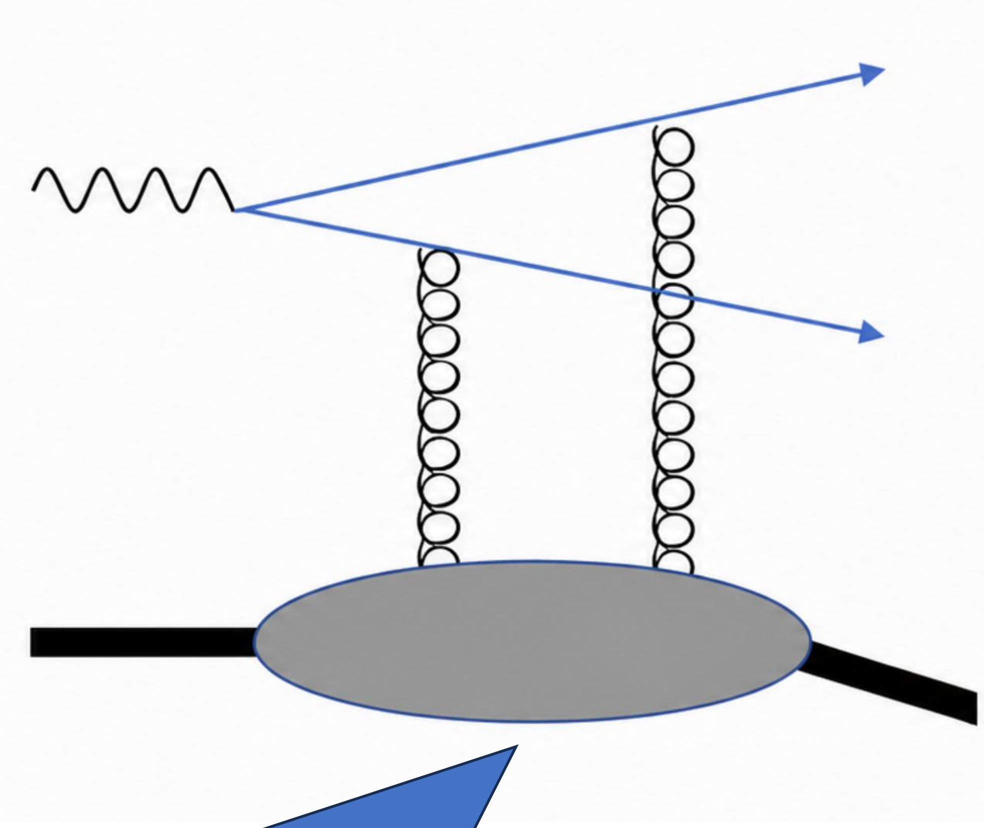
EIC能量： ~30%

能量越高，原子核相对被撞碎的几率越低：50%

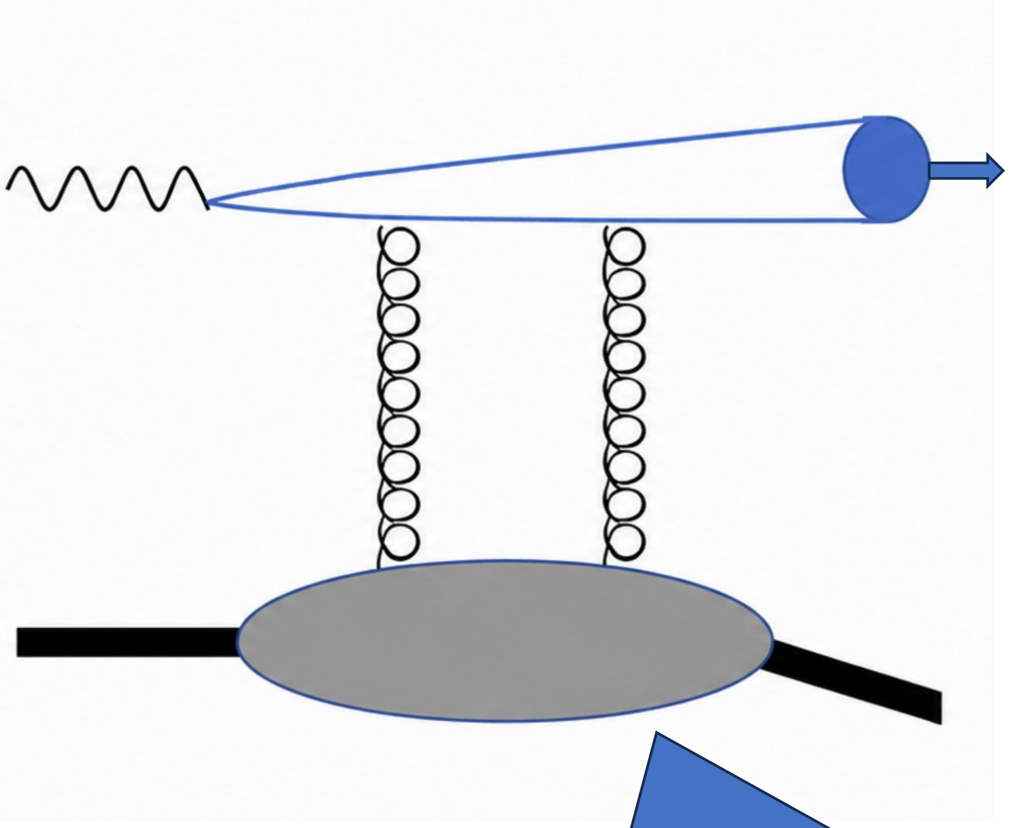
光学类比：



LHC上的相干衍射过程



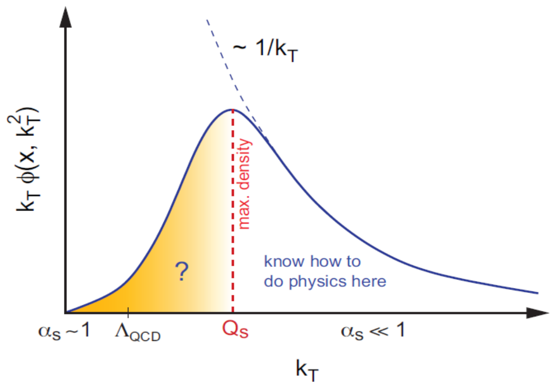
UPC中的衍射双喷注产生



UPC中的矢量介子产生

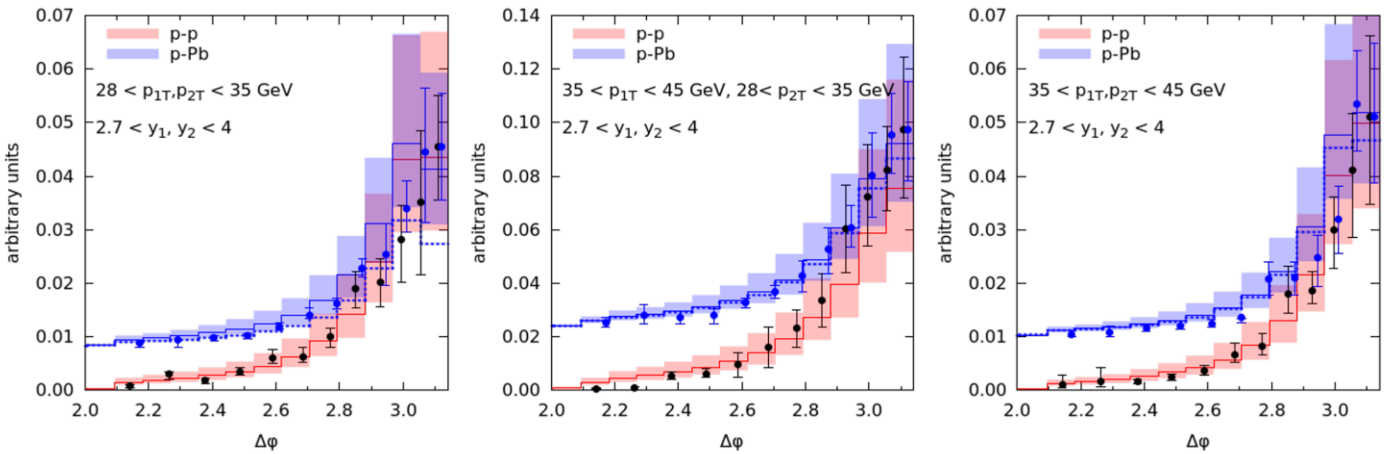
Di-jet/hadron de-correlation

更大的胶子横动量导致更大的imbalance:



需要用pp对撞做为基线

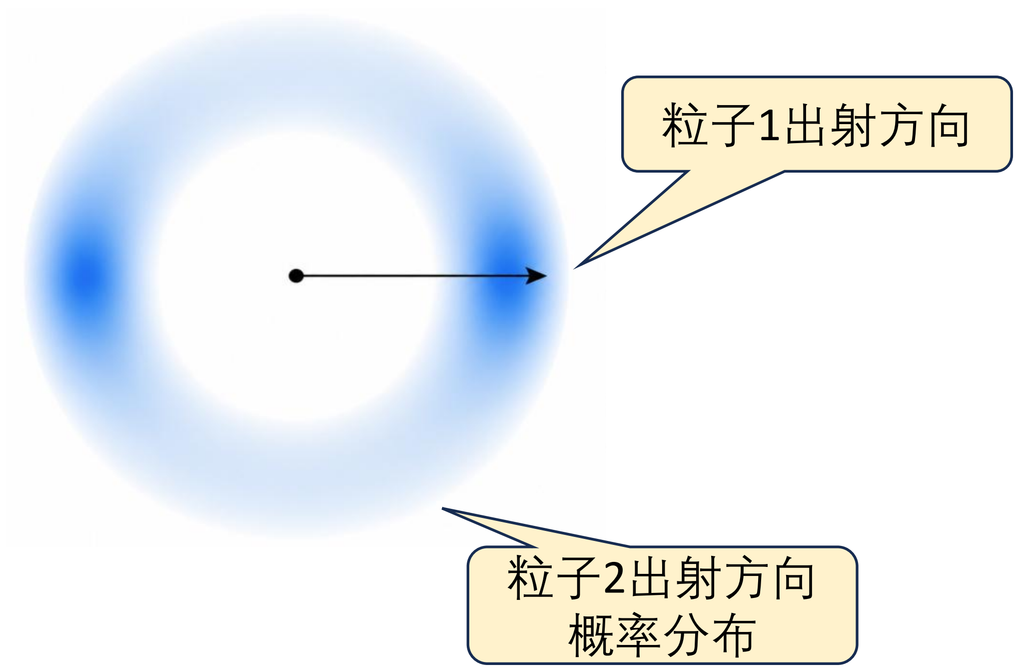
Forward dijets at the LHC:

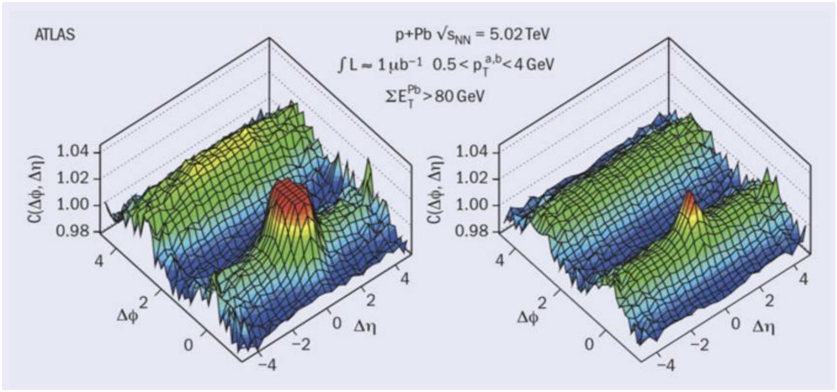


Hameren-Kakkad-Kotko-Kutak-Sapeta, 2023

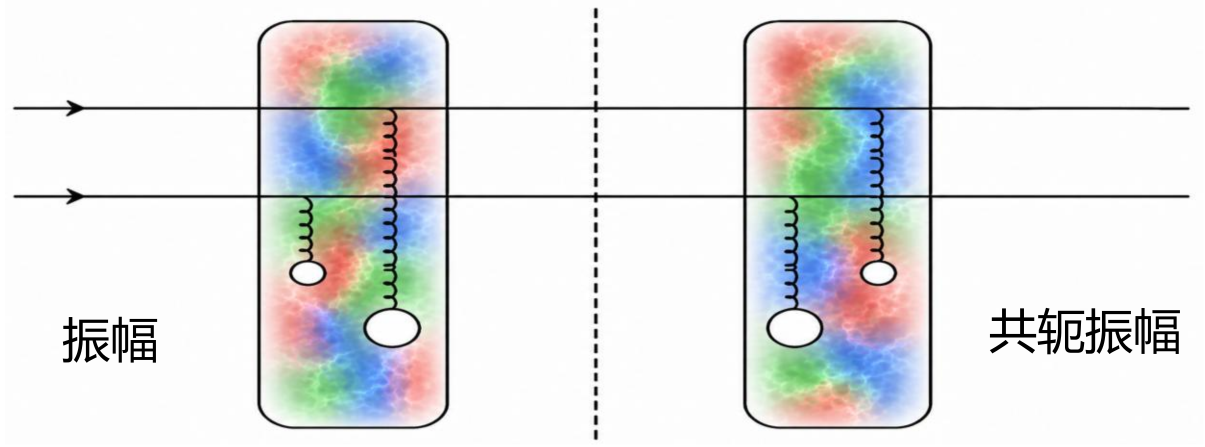
Ridge effect

2粒子倾向于沿相同方向出射:

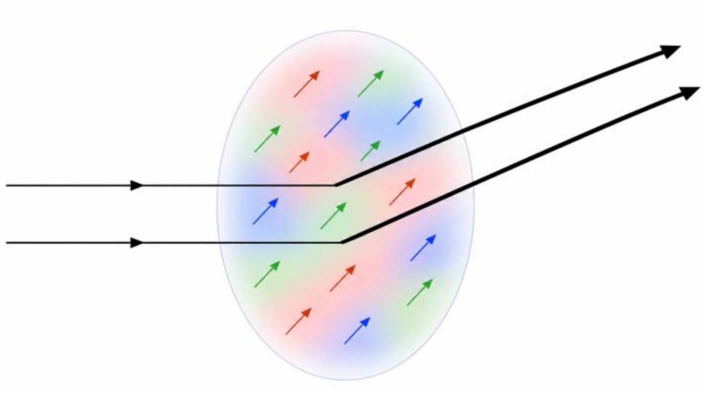




量子相干多重散射:



直觉物理解释:



被一个局域均匀色电场散射

另外两个非常有意思的观测量

Forward hadron production in pA collisions

博文的报告

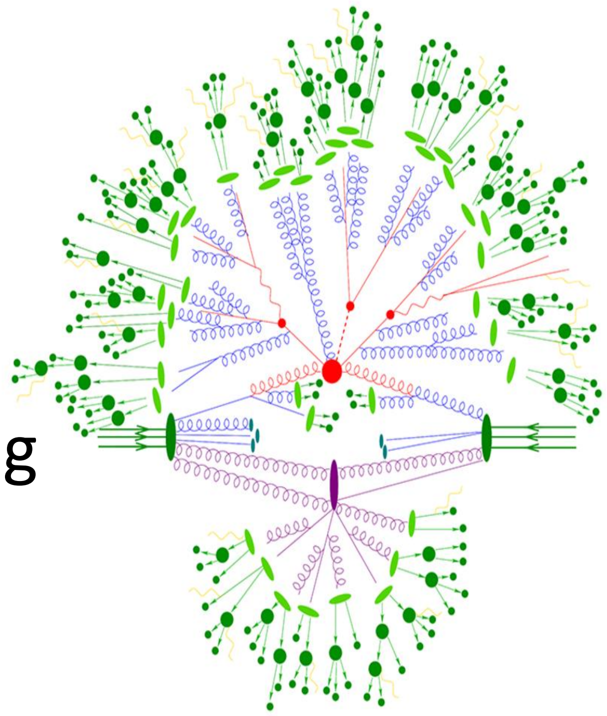
Nucleon energy energy correlation

晓辉的报告

Why parton shower generator

- Describe fully exclusive hadronic state
- Coherent branching
- Keep four momentum conservation in each branching
- Impact studies for future experiments

….

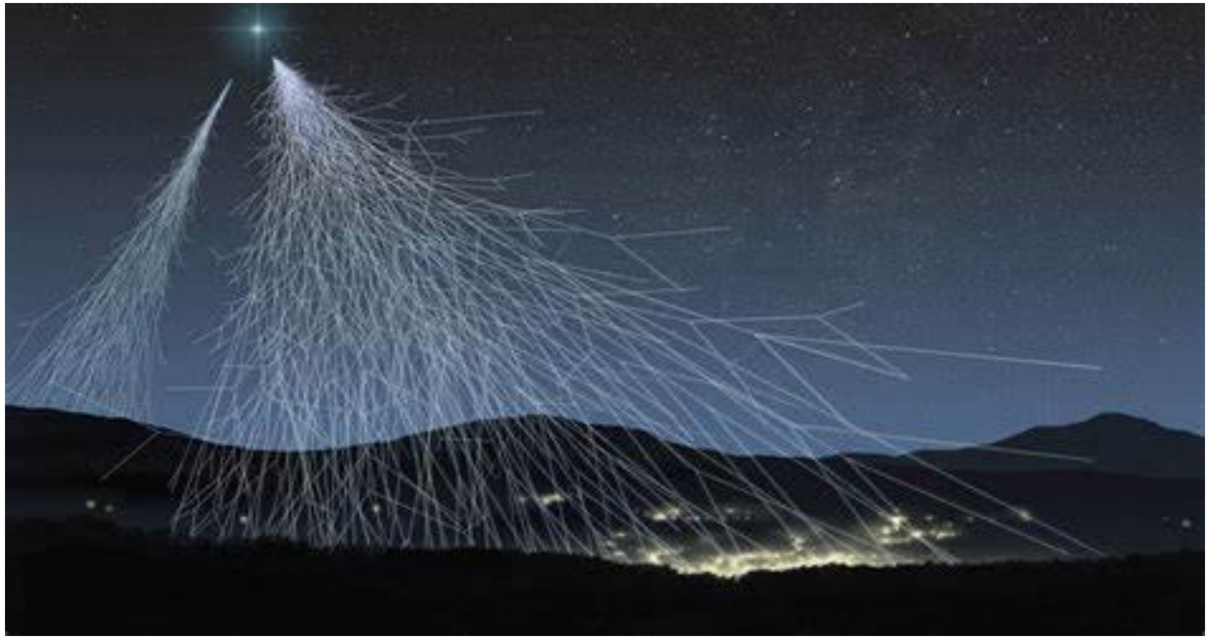


Why small *x* parton shower generator

- Saturation effect is absent in all existing generators

- Aim at developing a PS algorithm to be used:

- Phenomology in eA collisions @EIC
- Forward physics in pA collisions @LHC
- Cosmic ray event generator



Folded and unfolded GLR equation

- The standard GLR equation(unfolded one)

$$\frac{\partial N(\eta,k_\perp)}{\partial\eta}=\frac{\bar{\alpha}_s}{\pi}\left[\int\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp+l_\perp)-\int\frac{\mathrm{d}^2l_\perp}{(k_\perp-l_\perp)^2}\frac{k_\perp^2}{2l_\perp^2}N(\eta,k_\perp)\right]-\bar{\alpha}_sN^2(\eta,k_\perp)$$

- Resolved and unresolved branching:

$$\int\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp+l_\perp)\approx\int_\mu\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp+l_\perp)+\int_0^\mu\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp)$$

- Folded GLR equation: virtual correction is manifestly resumed to all orders

$$\frac{\partial}{\partial\eta}\frac{N(\eta,k_\perp)}{\Delta(\eta,k_\perp)}=\frac{\bar{\alpha}_s}{\pi}\int_\mu\frac{\mathrm{d}^2l_\perp}{l_\perp^2}\frac{N(\eta,l_\perp+k_\perp)}{\Delta(\eta,k_\perp)}$$

- Non-Sudakov form factor

$$\Delta(\eta,k_\perp)=\exp\left\{-\bar{\alpha}_s\int_{\eta_0}^{\eta}d\eta'\left[\ln\frac{k_\perp^2}{\mu^2}+N(\eta',k_\perp)\right]\right\}$$

Shi-Wei-ZJ, 2022

Parton shower algorithms

GLR v.s. DGLAP/CCFM

$$\Delta(\eta, k_\perp) = \exp\left\{-\bar{\alpha}_s \int_{\eta_0}^{\eta} d\eta' \left[\ln\frac{k_\perp^2}{\mu^2} + N(\eta', k_\perp)\right]\right\}$$

$$\Delta_a(t, t') = \exp\left\{-\sum_{b\in\{q,g\}} \int_t^{t'} \frac{\mathrm{d}\bar{t}}{\bar{t}} \int_{z_{\min}}^{z_{\max}} \mathrm{d}z\, \frac{\alpha_s}{2\pi} \frac{1}{2} P_{ab}(z)\right\}$$

GLR	DGLAP/CCFM
gluon splitting gluon fusion	parton splitting

The evolution variable:

GLR	DGLAP/CCFM
$\eta = \ln(1/x)$	Q

The generated event:

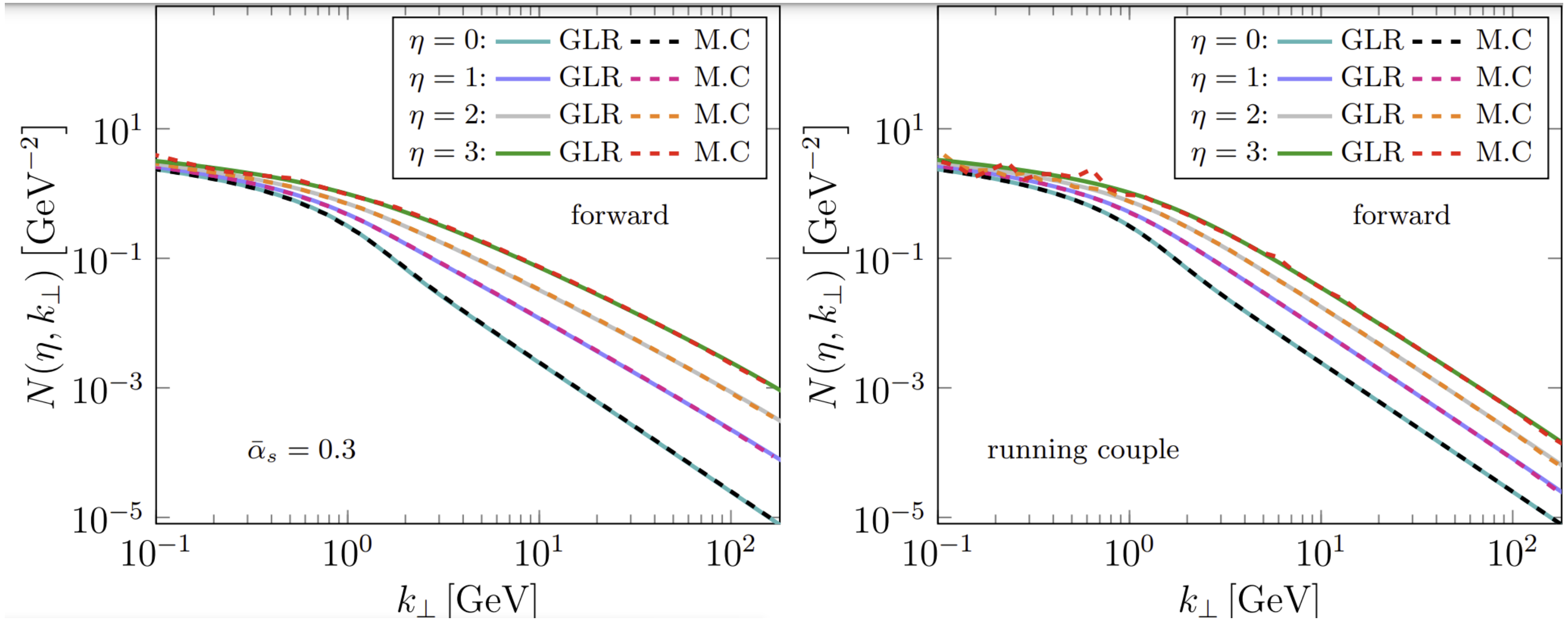
GLR	DGLAP/CCFM
reweight	Unitary

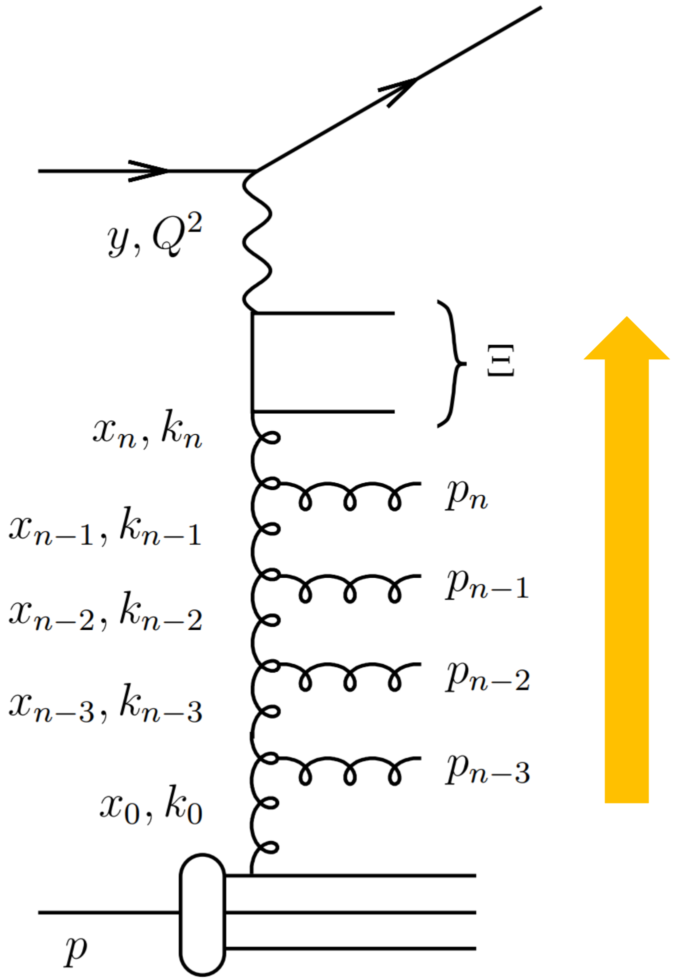
Forward evolution

- MV model as the initial condition at x_0=0.01:

$$N(\eta=0,k_\perp)=\int\frac{d^2r_\perp}{2\pi}e^{-ik_\perp\cdot r_\perp}\frac{1}{r_\perp^2}\left(1-\exp[-\frac{1}{4}Q_{s0}^2r_\perp^2\ln(e+\frac{1}{\Lambda r_\perp})]\right)$$

- Test the algorithm



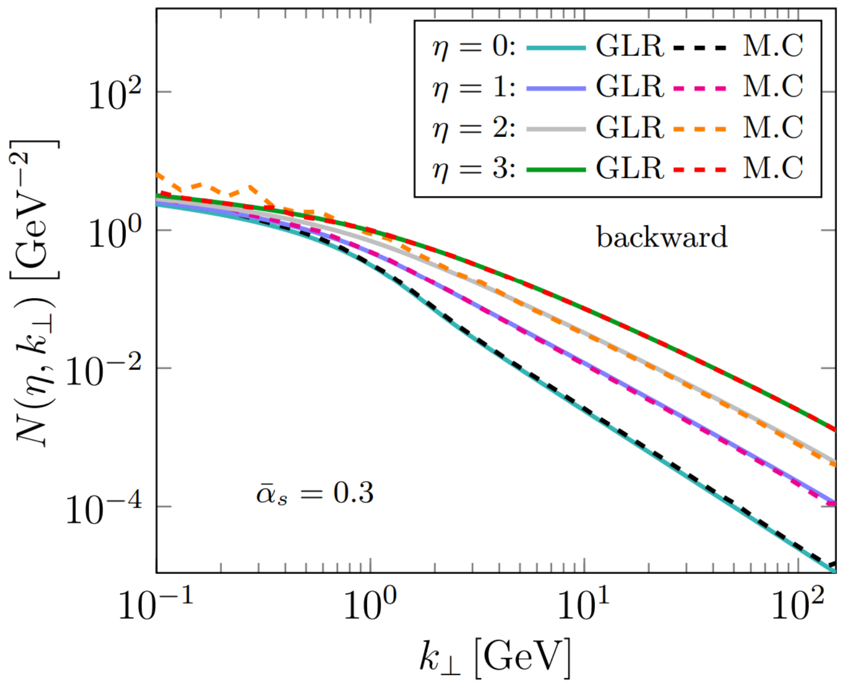


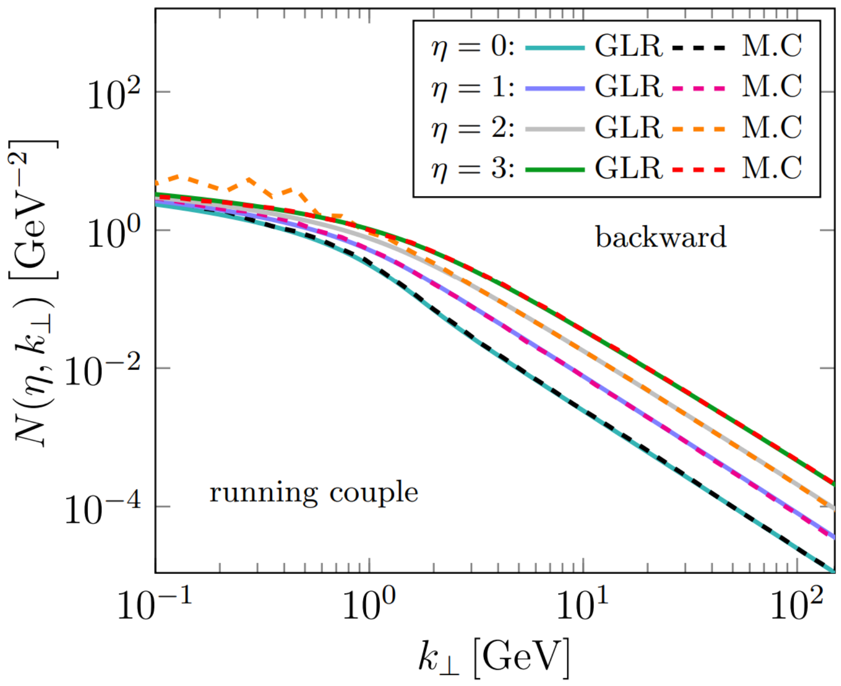
Backward evolution

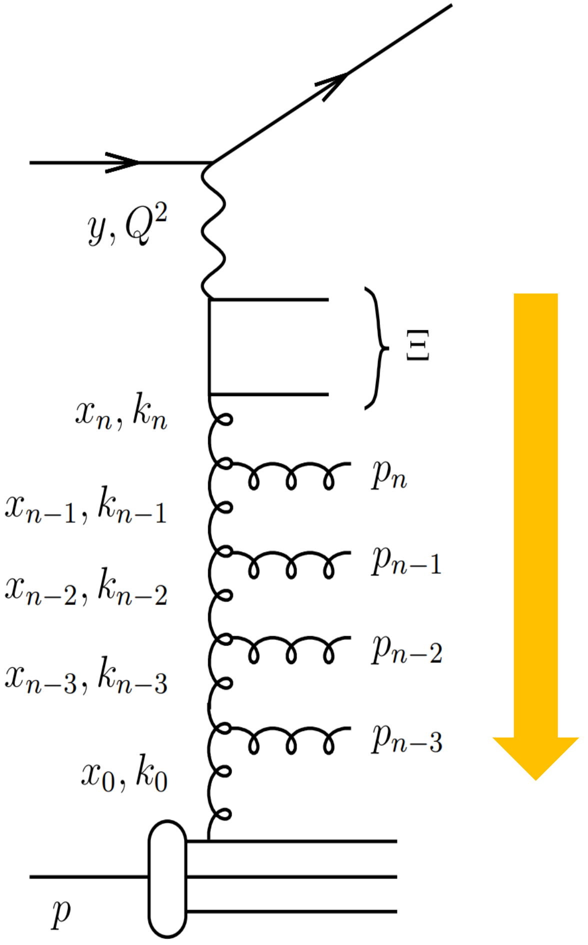
- **Non-Sudakov form factor:**

$$\frac{\Delta(\eta_{i+1},k_{\perp,i+1})N(\eta_i,k_{\perp,i+1})}{\Delta(\eta_i,k_{\perp,i+1})N(\eta_{i+1},k_{\perp,i+1})} = \exp\left[-\frac{\bar{\alpha}_s}{\pi}\int_{\eta_i}^{\eta_{i+1}} d\eta \int_\mu \frac{d^2 l_\perp}{l_\perp^2}\frac{N(\eta,k_{\perp,i+1}+l_\perp)}{N(\eta,k_{\perp,i+1})}\right]$$

  - $l_\perp$ **is also sampled in a different way!**

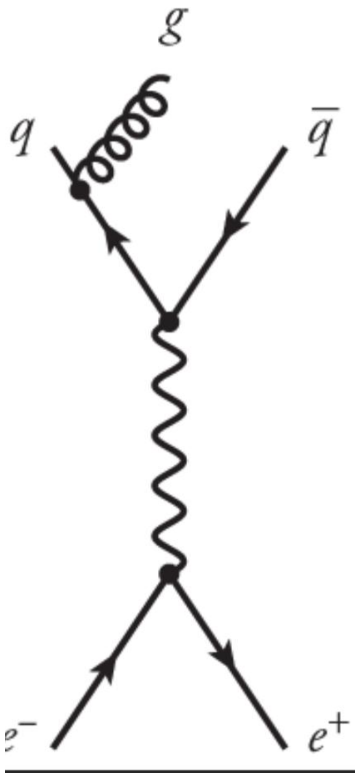




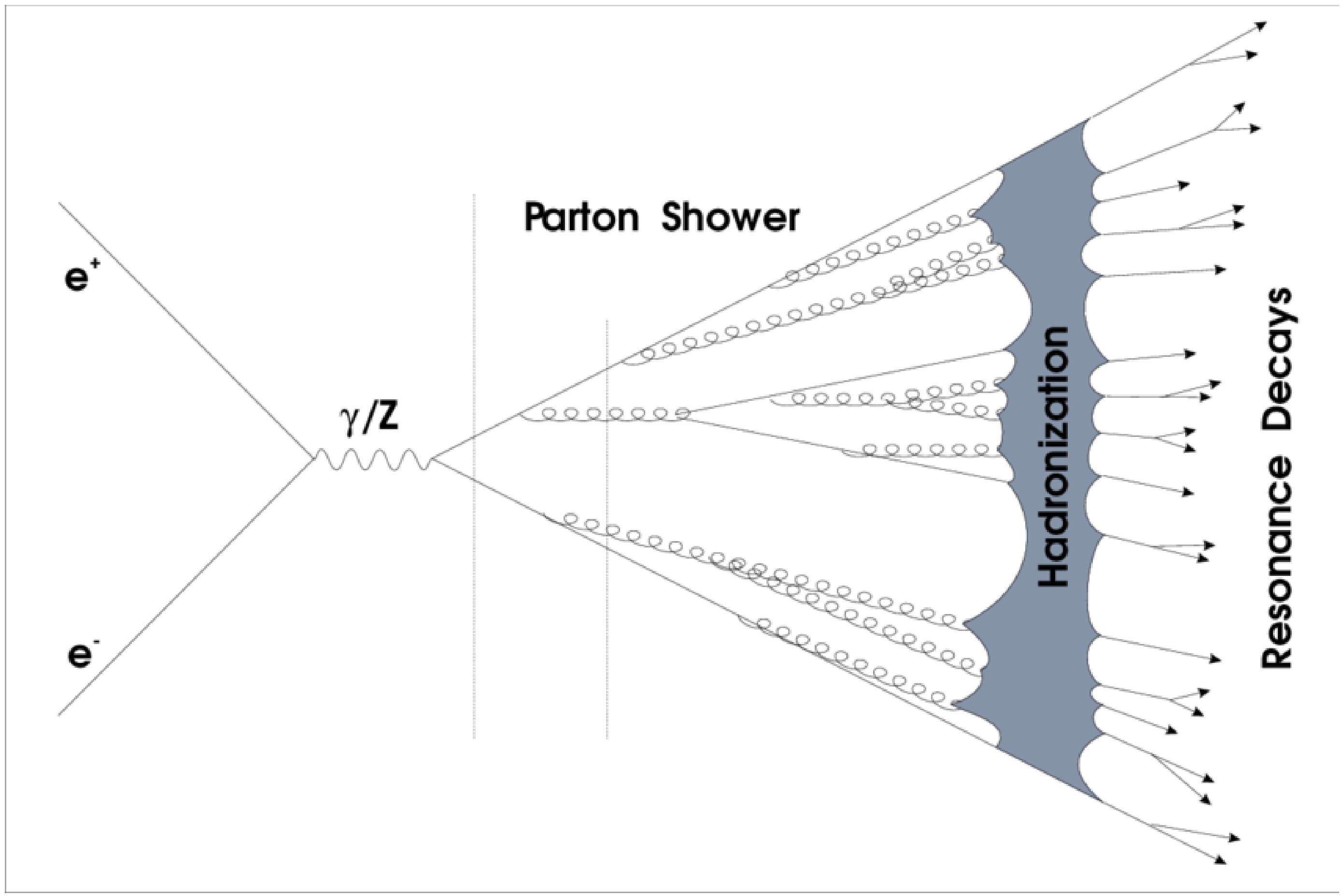


Kinematic constraint & Coherent branching

- The Chudakov effect



- Angular ordering



➢ Wide angle radiation suppressed!

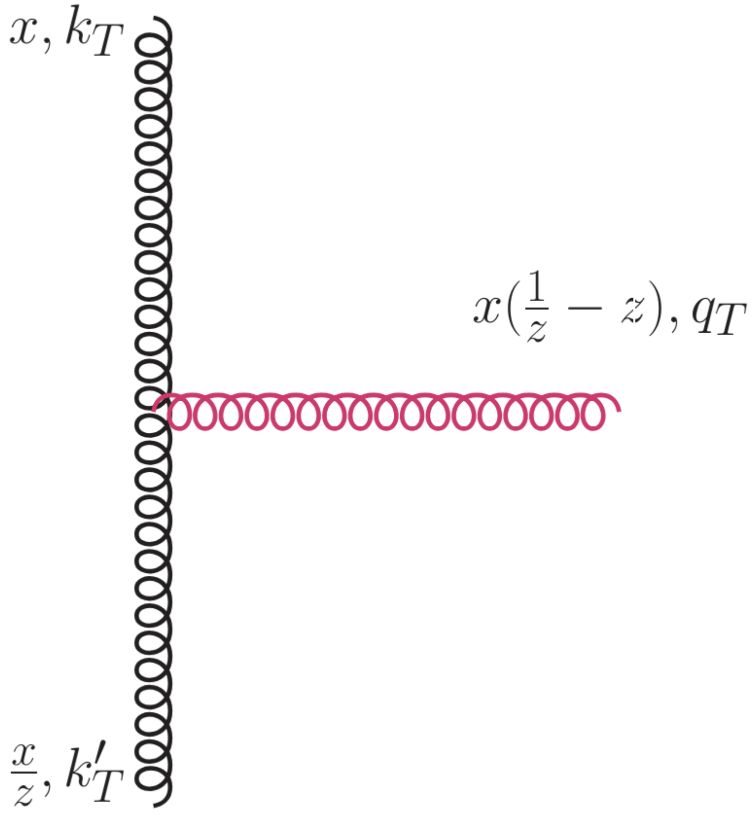
Kinematical constraint in the GLR evolution equation

[Kwiecinski, Martin, Sutton, Z. Phys. C, 96;
Deak, Kutak, Li, Stasto, EPJC, 19]

- **The virtuality of t-channel gluon should be dominated by transverse components**

$$k_T^2 > |k^+ k^-| \qquad k^- = k'^- - q^- \simeq -q^- = -q_T^2/q^+$$

$$k^+ k^- \simeq -\frac{k^+}{q^+} q_T^2 = -\frac{k^+}{k'^+ - k^+} q_T^2 = -\frac{z}{1-z} q_T^2$$



- **The on shell condition for s-channel gluon leads to the constraint**

$$q_T^2 < \frac{1-z}{z} k_T^2 \qquad \eta \longrightarrow \eta + \ln \frac{k_\perp^2}{k_\perp^2 + l_\perp^2}$$

- **Results in a non-local GLR equation**

$$\frac{\partial N(\eta, k_\perp)}{\partial \eta} = \frac{\bar{\alpha}_s}{\pi} \int \frac{\mathrm{d}^2 l_\perp}{l_\perp^2} N\left(\eta + \ln \frac{k_\perp^2}{k_\perp^2 + l_\perp^2}, l_\perp + k_\perp\right) - \frac{\bar{\alpha}_s}{\pi} \int_0^{k_\perp} \frac{\mathrm{d}^2 l_\perp}{l_\perp^2} N(\eta, k_\perp) - \bar{\alpha}_s N^2(\eta, k_\perp)$$

Coherent branching in the GLR evolution

- Kinematic constrained GLR equation

$$\frac{\partial}{\partial\eta}\frac{N(x,k_\perp)}{\Delta(\eta,k_\perp)}=\frac{\bar{\alpha}_s}{\pi}\int_\mu\frac{\mathrm{d}^2l_\perp}{l_\perp^2}\frac{N\left(\eta+\ln\left[\frac{k_\perp^2}{k_\perp^2+l_\perp^2}\right],l_\perp+k_\perp\right)}{\Delta(\eta,k_\perp)}$$

Shi-Wei-ZJ, 2022

- Weighting factor for forward evolution:

$$\mathcal{W}_{kc}(\eta_i,\eta_{i+1};k_\perp)=\frac{(\eta_{i+1}-\eta_i)\int_\mu^{\min\left[P_\perp,\sqrt{(k_\perp-l_\perp)^2\frac{1-z}{z}}\right]}\frac{\mathrm{d}^2l_\perp}{l_\perp^2}e^{-\bar{\alpha}_s\int_{\eta_{i+1}}^{\eta_{i+1}+\ln\frac{(k_\perp-l_\perp)^2}{(k_\perp-l_\perp)^2+l_\perp^2}}\mathrm{d}\eta\left[\ln\frac{k_\perp^2}{\mu^2}+N(\eta,k_\perp)\right]}}{(\eta_{i+1}-\eta_i)\ln\frac{k_\perp^2}{\mu^2}+\int_{\eta_i}^{\eta_{i+1}}d\eta N(\eta,k_\perp)}$$

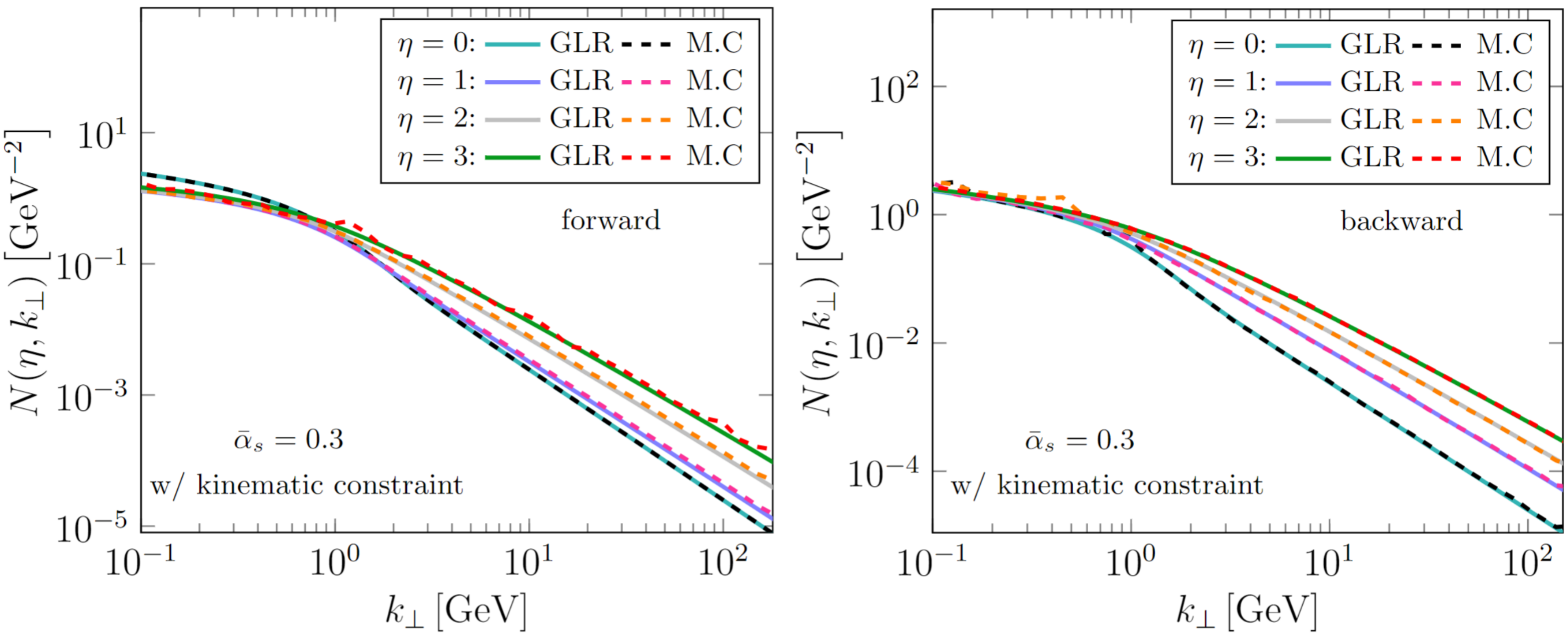
- Weighting factor for backward evolution:

$$\mathcal{W}(\eta_{i+1},\eta_i;k_{\perp,i+1})=\frac{(\eta_{i+1}-\eta_i)\ln\frac{k_{\perp,i}^2}{\mu^2}+\int_{\eta_i}^{\eta_{i+1}}d\eta\mathcal{N}(\eta,k_{\perp,i})}{(\eta_{i+1}-\eta_i)\ln\frac{P_\perp^2}{\mu^2}}\frac{N(\eta_i,k_{\perp,i})}{N\left(\eta_i+\ln\left[\frac{k_{\perp,i+1}^2}{k_{\perp,i+1}^2+l_\perp^2}\right],k_{\perp,i}\right)}$$

- Non-Sudakov factor for backward evolution

$$\frac{\Delta(\eta_{i+1},k_{\perp,i+1})N(\eta_i,k_{\perp,i+1})}{\Delta(\eta_i,k_{\perp,i+1})N(\eta_{i+1},k_{\perp,i+1})}=\exp\left[-\frac{\bar{\alpha}_s}{\pi}\int_{\eta_i}^{\eta_{i+1}}\mathrm{d}\eta\int_\mu^{\min\left[P_\perp,\sqrt{\frac{1-z}{z}k_{\perp,i+1}^2}\right]}\frac{\mathrm{d}^2l_\perp}{l_\perp^2}\frac{N\left(\eta+\ln\left[\frac{k_{\perp,i+1}^2}{k_{\perp,i+1}^2+l_\perp^2}\right],k_{\perp,i+1}+l_\perp\right)}{N(\eta,k_{\perp,i+1})}\right]$$

Coherent branching: test against the numerical results



Shi-Wei-ZJ, 2022

Joint small x and kt resummation

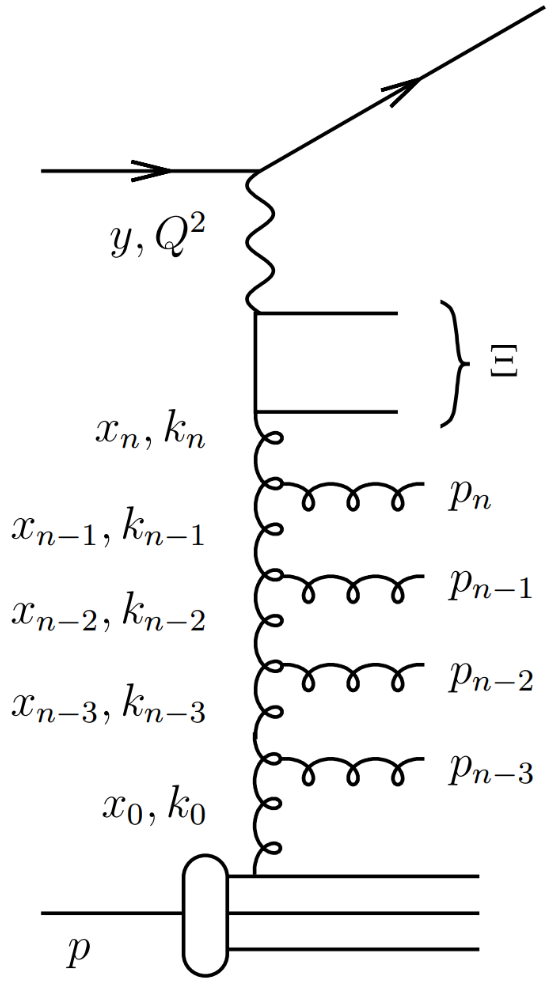
- When $S >> Q^2 >> k_T^2$, resume two type large logs

$$\ln \frac{S}{Q^2} \qquad \ln^2 \frac{Q^2}{k_\perp^2}$$

- Starting point:

$$xG(x,l_\perp,x\zeta) = \int \frac{dy^- d^2 y_\perp}{(2\pi)^3 P^+} e^{-ixP^+y^- + il_\perp \cdot y_\perp} \langle P | F_\mu^+(y^-, y_\perp) \mathcal{L}_{\tilde{n}}^\dagger (y^-, y_\perp) \mathcal{L}_{\tilde{n}}(0, 0_\perp) F^{\mu+}(0) | P \rangle$$

Collins, Soper, 81; Collins, Soper, Sterman, 85



Gloun---->gloun splitting kernel; $\mathcal{P}_{gg}(z) = 2C_A \frac{(z^2 - z + 1)^2}{z(1-z)}$

When z(or x) --->0, large logarithm $\ln \frac{1}{x}$ summed by BFKL

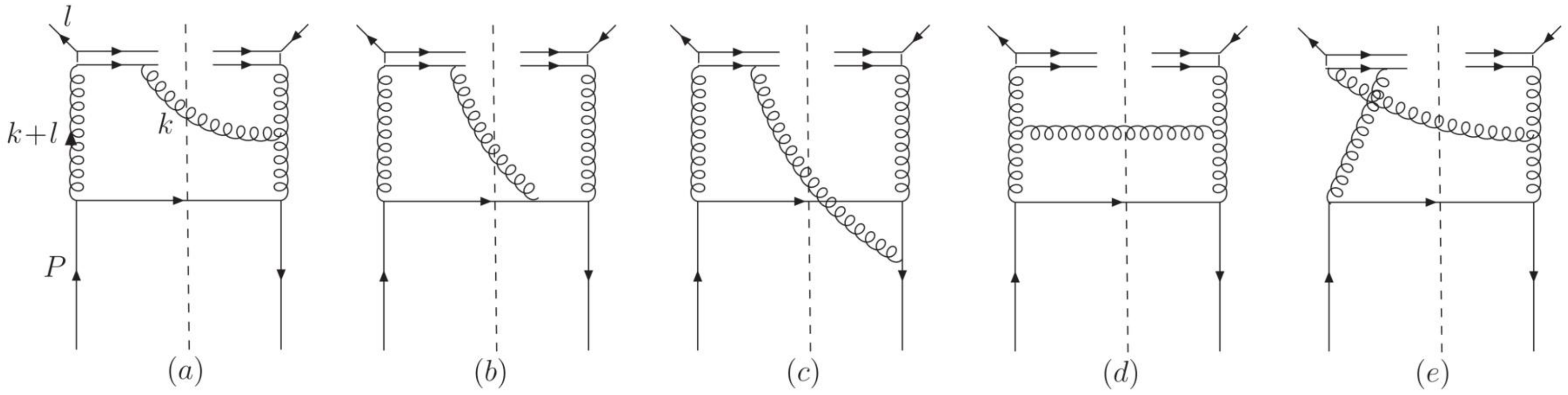
When z--->1, light cone divergence, introduce ζ to regularize

large logarithm $\ln \frac{x^2 \varsigma^2}{k_T^2}$ summed by CS

Mueller, Xiao, Yuan 2012; Xiao, Yuan, Zhou, 2017; Caucal, Salazar, Schenke, Venugopalan, 2022-2023; Taels, Altinoluk, Beuf, Marquet, 2022; Mukherjee, Skokov, Tarasov, Tiwari, 2023….

Formulation in terms of gluon TMD(dilute limit)

- Sample real diagrams



- The resulting gluon TMD indeed simultaneously satisfies the both

$$\int_0^\infty \frac{dk^+}{k^+} = \int_{l^+}^\infty \frac{dk^+}{k^+} + \int_0^{l^+} \frac{dk^+}{k^+}$$

2016, ZJ

BFKL equation:

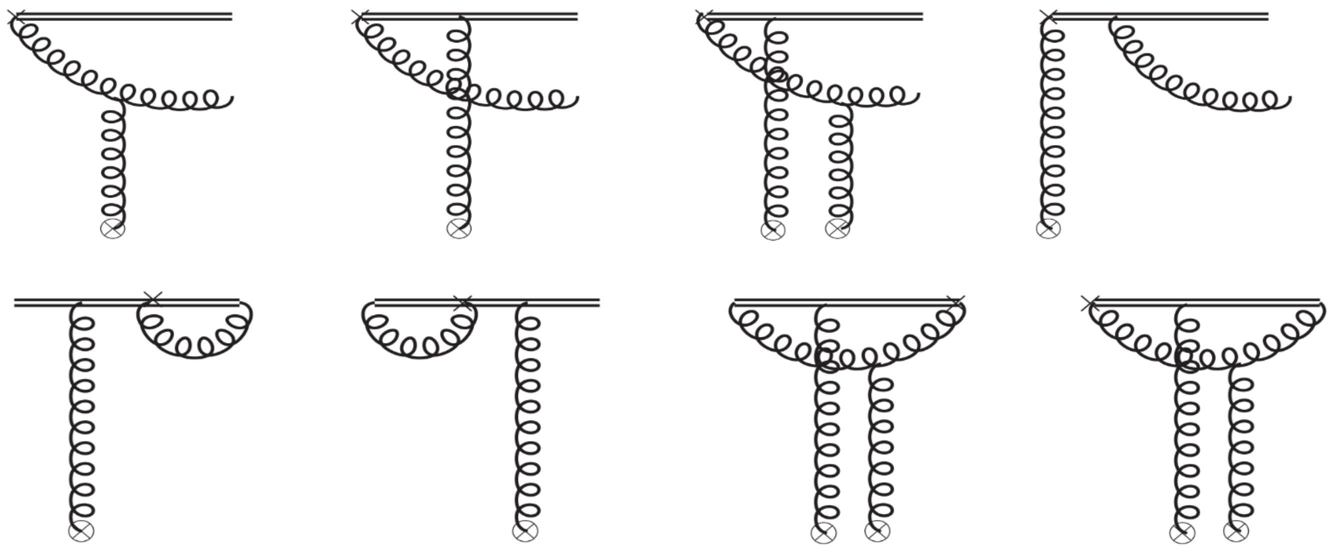
$$\frac{\partial\left[xG(x,l_\perp,x\zeta)\right]}{\partial \ln(1/x)} = \frac{\alpha_s N_c}{\pi^2}\int \frac{d^2k_\perp}{k_\perp^2}\left\{xG(x,k_\perp+l_\perp,x\zeta) - \frac{l_\perp^2}{2(l_\perp+k_\perp)^2}xG(x,l_\perp,x\zeta)\right\}$$

CS equation:

$$\frac{\partial\left[G(x,b_\perp,x\zeta)\right]}{\partial \ln\zeta} = -\frac{\alpha_s N_c}{\pi}\ln\left[\frac{x^2\zeta^2 b_\perp^2}{4}e^{2\gamma_E-\frac{1}{2}}\right]G(x,b_\perp,x\zeta)$$

Small x TMDs in CGC at NLO(double log)

Sample diagrams **(Collins-2011 scheme)**



Xiao, Yuan and ZJ, 2017.

The basic nonperturbative ingredient:

$$U(x_\perp) = \langle \mathcal{P} e^{-ig\int_{-\infty}^{+\infty} dx^- A^+(x^-,\, x_\perp)} \rangle$$

Multiple gluon rescattering is treated in an equal way.

Collinear approach v.s. CGC

- Collinear factorization:

$$\tilde{f}_g^{(sub.)}(x, r_\perp, \zeta_c{}') = e^{-S^g_{pert}(Q, r_\perp)} \sum_i C_{g/i}(\mu_r/\mu) \otimes f_i(x, \mu)$$

Sudakov factor

Hard coefficient

Colliner PDF

- CGC**(Colliner divergence absent)**

$$xG^{(1)}(x, k_\perp, \zeta) = -\frac{2}{\alpha_S} \int \frac{d^2x_\perp d^2y_\perp}{(2\pi)^4} e^{ik_\perp \cdot r_\perp} \mathcal{H}^{WW}(\alpha_s(Q)) e^{-S_{sud}(Q^2, r_\perp^2)} \mathcal{F}^{WW}_{Y=\ln 1/x}(x_\perp, y_\perp)$$

Hard coefficient

Sudakov factor

Two point function

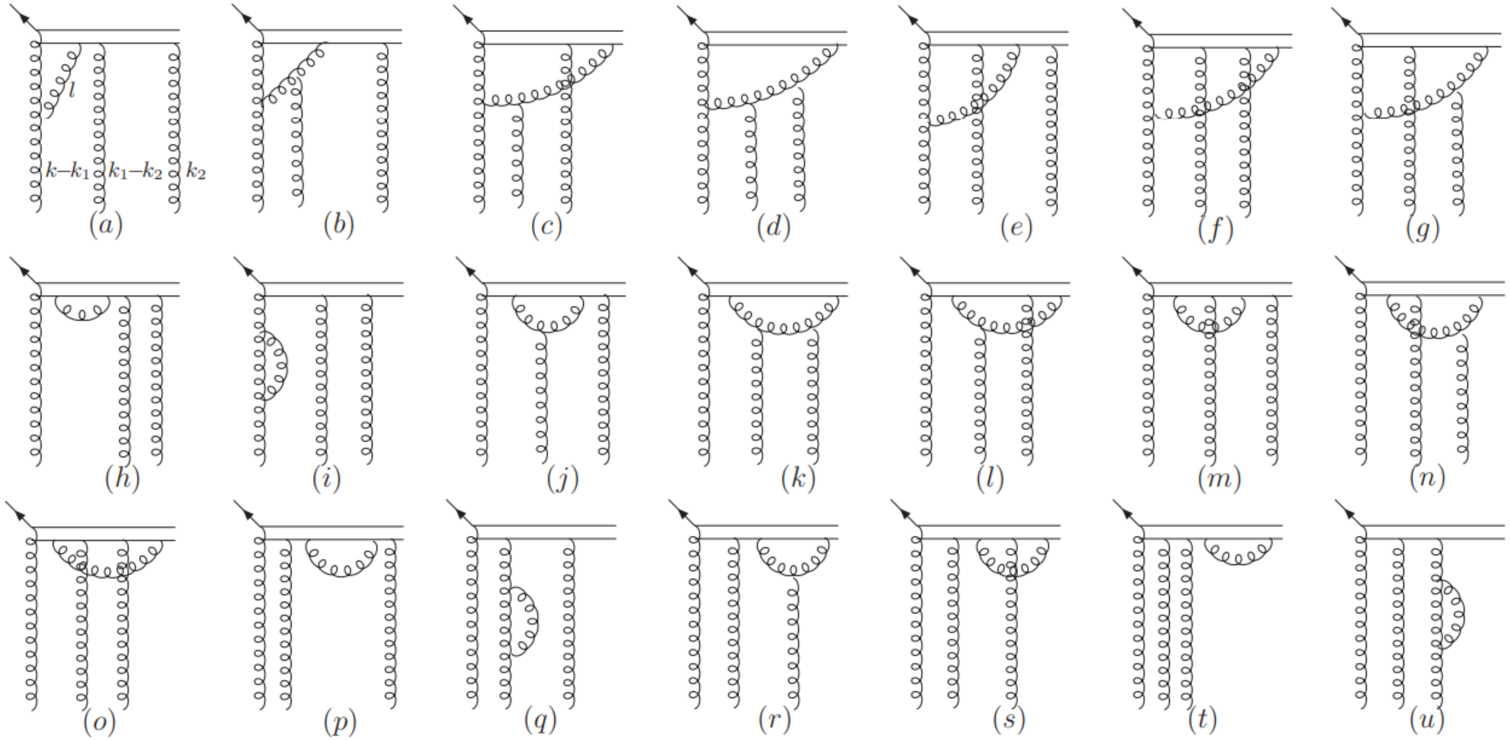
Two step evolution: $x_0 \longrightarrow x$ $\quad k_t \longrightarrow Q$

Sudakov Single log at small x

The anomalous dimension at small x?

$$\frac{\mathrm{d}\ \ln G(x, b_\perp, \mu^2, \zeta_c^2)}{\mathrm{d}\ \ln\mu} = \gamma_G\left(g(\mu), \zeta_c^2/\mu^2\right)$$

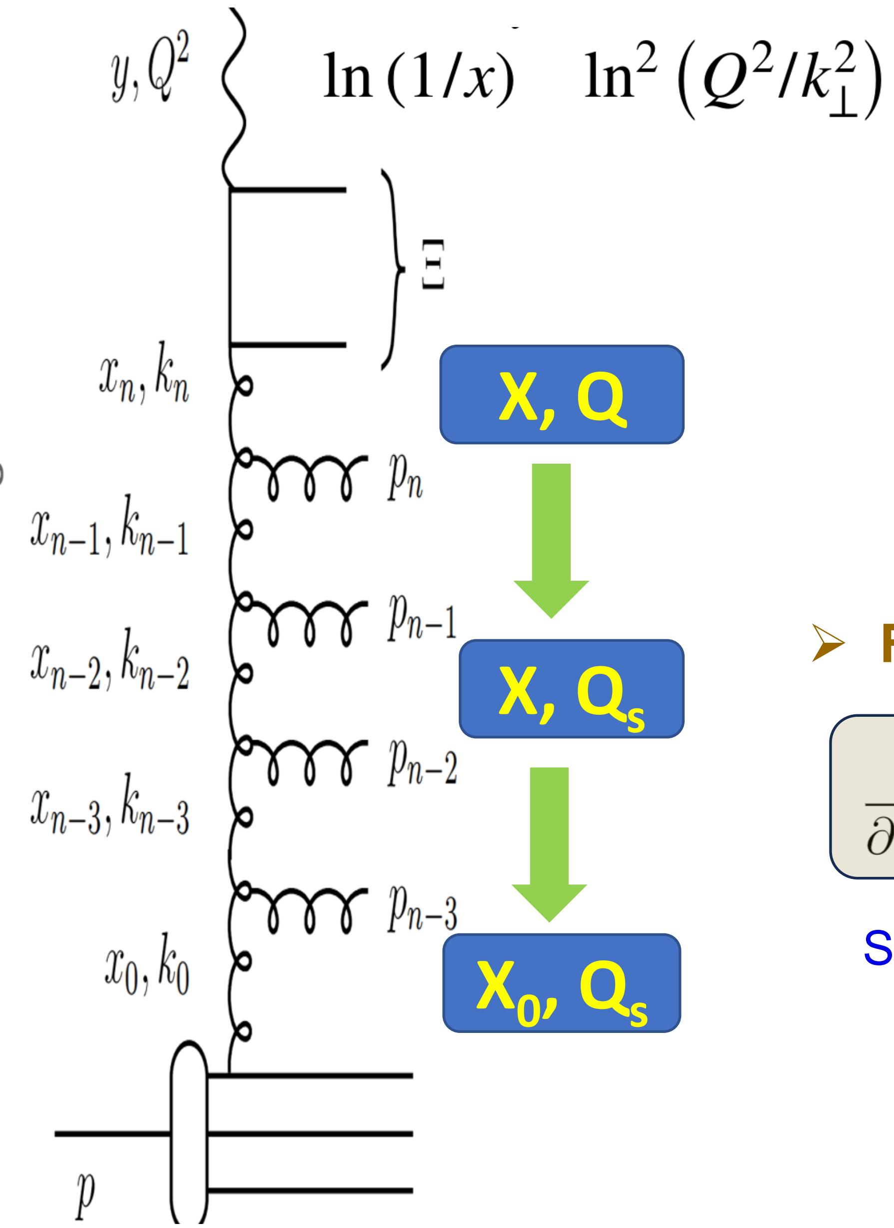
Compute UV part first; employ the Eikonal approximation next!



2019, ZJ

- Single log is not affected by saturation effect.

Monte Carlo implementation of the joint resummation



- Combing Collins-Soper equation

$$\frac{\partial N(\mu^2,\zeta^2,x,k_\perp)}{\partial \ln \zeta^2} = \frac{2\alpha_s N_c}{\pi^2}\int_0^{\zeta} \frac{d^2 l_\perp}{l_\perp^2}\left[N(\mu^2,\zeta^2,x,k_\perp+l_\perp) - N(\mu^2,\zeta^2,x,k_\perp)\right]$$

with renormalization group equation

$$\frac{\partial N(\mu^2,\zeta^2,x,k_\perp)}{\partial \ln \mu^2} = \frac{\alpha_s N_c}{\pi}\left[\frac{\beta_0}{6} - \ln\frac{\zeta^2}{\mu^2}\right] N(\mu^2,\zeta^2,x,k_\perp)$$

- **Folded CS+RG:** $N(Q^2,x,k_\perp) \equiv N(\mu^2 = Q^2, \zeta^2 = Q^2, x, k_\perp)$

$$\frac{\partial}{\partial \ln Q^2}\frac{N(Q^2,x,k_\perp)}{\Delta_s(Q^2,k_\perp)} = \frac{2\bar{\alpha}_s}{\pi}\int_{Q_0}^{Q}\frac{d^2 l_\perp}{l_\perp^2}\frac{N(Q^2,x,k_\perp+l_\perp)}{\Delta_s(Q^2,k_\perp)}$$

Shi-Wei-ZJ, 2023

Sudakov form factor

$$\Delta_s(Q^2,k_\perp) = \exp\left[-\bar{\alpha}_s\int_{Q_0^2}^{Q^2}\frac{dt}{t}\left(2\ln\frac{t}{Q_0^2} - \frac{\beta_0}{6}\right)\right]$$

Monte Carlo implementation of kt resummation

- The modified Sudakov factor in the backward evolution:

$$\frac{\Delta_s(Q_n^2,k_{\perp,n})N(Q_{n-1}^2,x_n,k_{\perp,n})}{\Delta_s(Q_{n-1}^2,k_{\perp,n})N(Q_n^2,x_n,k_{\perp,n})}=\exp\left[-\int_{Q_{n-1}^2}^{Q_n^2}\frac{dt}{t}\int_{Q_0}^{t}\frac{d^2l_\perp}{l_\perp^2}\frac{2\bar{\alpha}_s(l_\perp^2)}{\pi}\frac{N(t,x_n,k_{\perp,n}+l_\perp)}{N(t,x_n,k_{\perp,n})}\right]=\mathcal{R}$$

- Sample lt and reconstruct z

Shi-Wei-ZJ, 2023

$$\int\frac{d^2l_\perp}{l_\perp^2}\frac{\bar{\alpha}_s(l_\perp^2)}{\pi}N(Q_{n-1}^2,x_n,k_{\perp,n}+l_\perp)\qquad l_{\perp,n}^2\approx Q_{n-1}^2(1-z_n)$$

- Weight factor

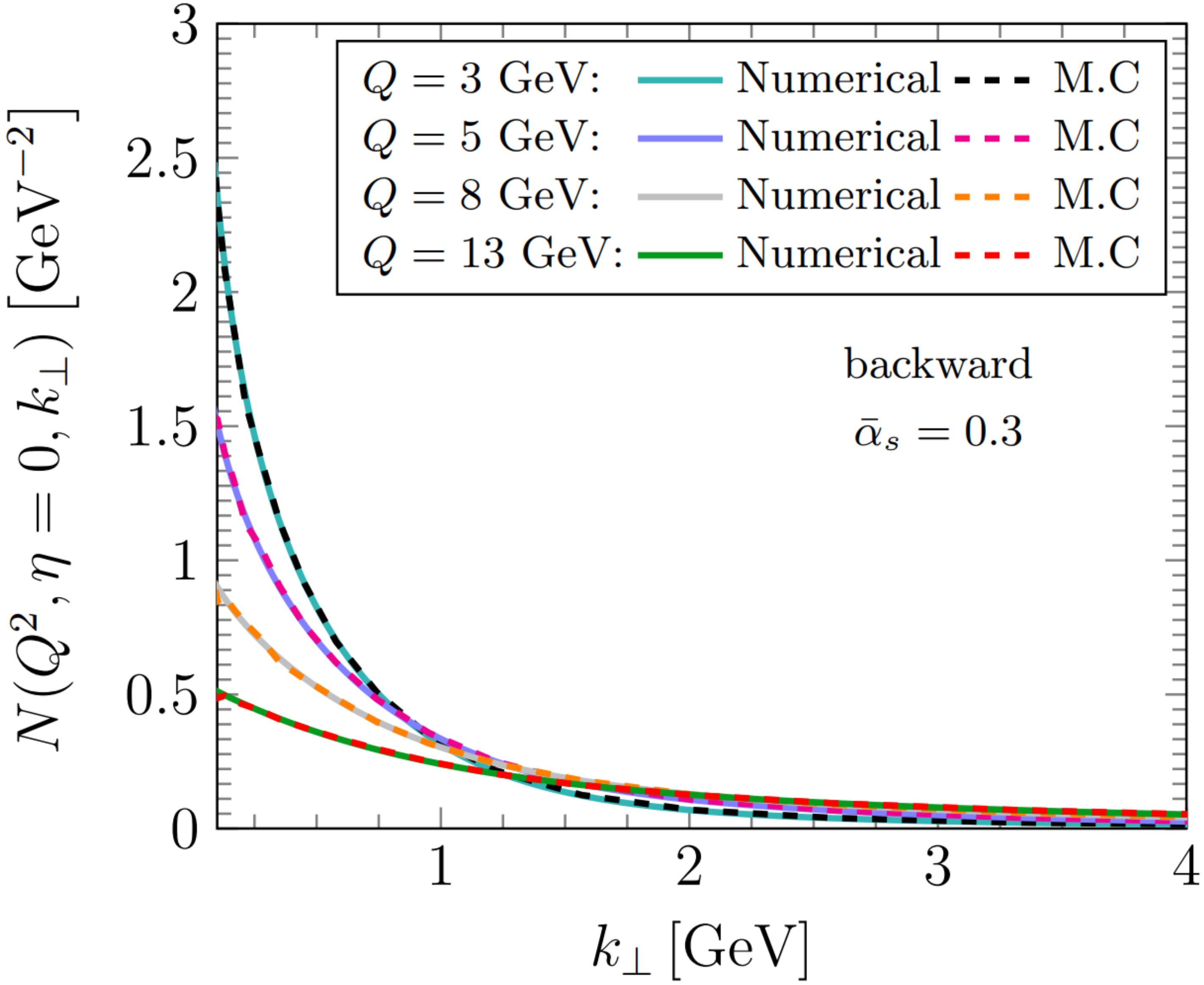
$$\mathcal{W}=\frac{\int_{Q_{n-1}^2}^{Q_n^2}\frac{dt}{t}\ln\frac{t^2}{Q_0^2}}{\int_{Q_{n-1}^2}^{Q_n^2}\frac{dt}{t}\left[\ln\frac{t^2}{Q_0^2}-\frac{\beta_0}{12}\right]}$$

- Unitary is preserved only within the double leading log approximation

- Terminate kt PS and turn on small x PS

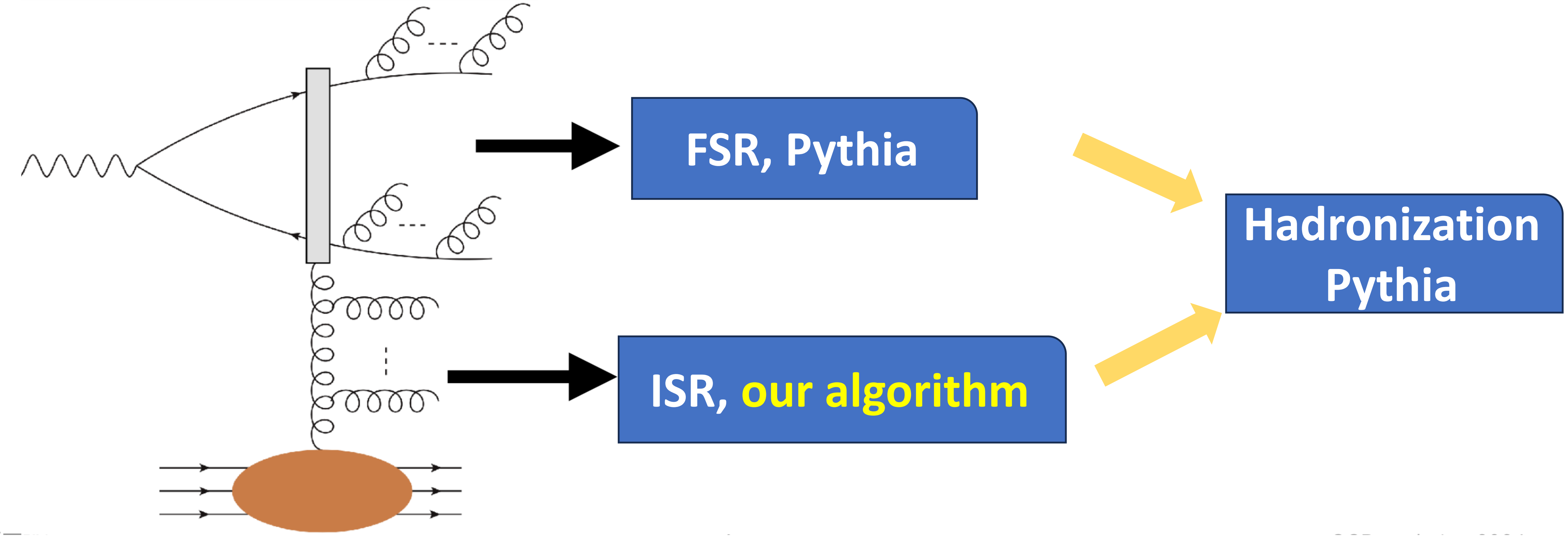
Z_i>0.5 Q_i>Q_s

Numerical V.S. MC:



Initial condition: $$N(Q_0^2 = 1\ \text{GeV}^2, x = 0.01, k_\perp) = \int \frac{d^2 r_\perp}{2\pi} e^{ik_\perp \cdot r_\perp} \frac{1}{r_\perp^2}\left[1 - e^{-\frac{Q_s^2 r_\perp^2}{4}\log\left(\frac{1}{r_\perp \Lambda_{\text{MV}}} + e\right)}\right]$$

Hadronization and final state radiations



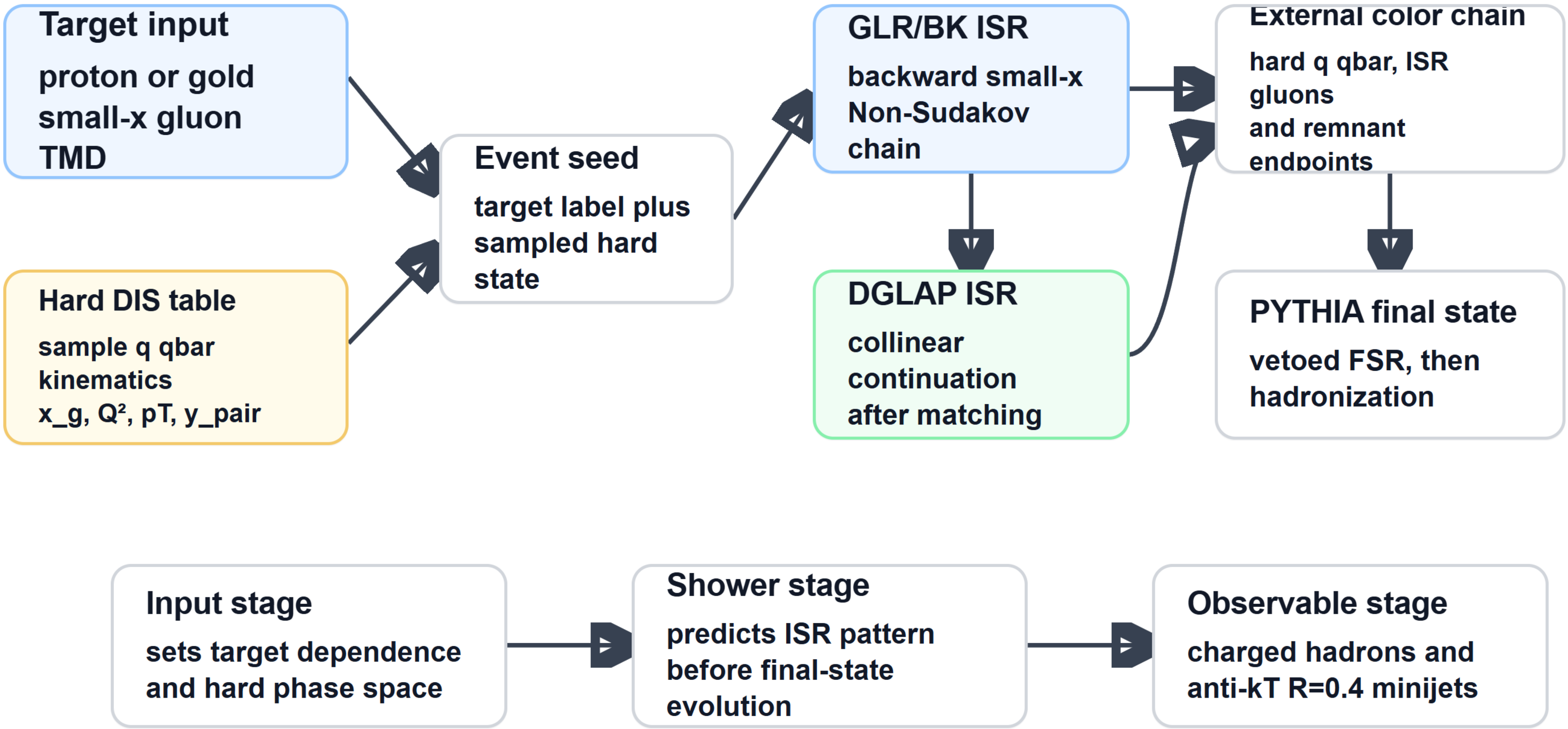
Jian Zhou

@zzzhoujian · Plus

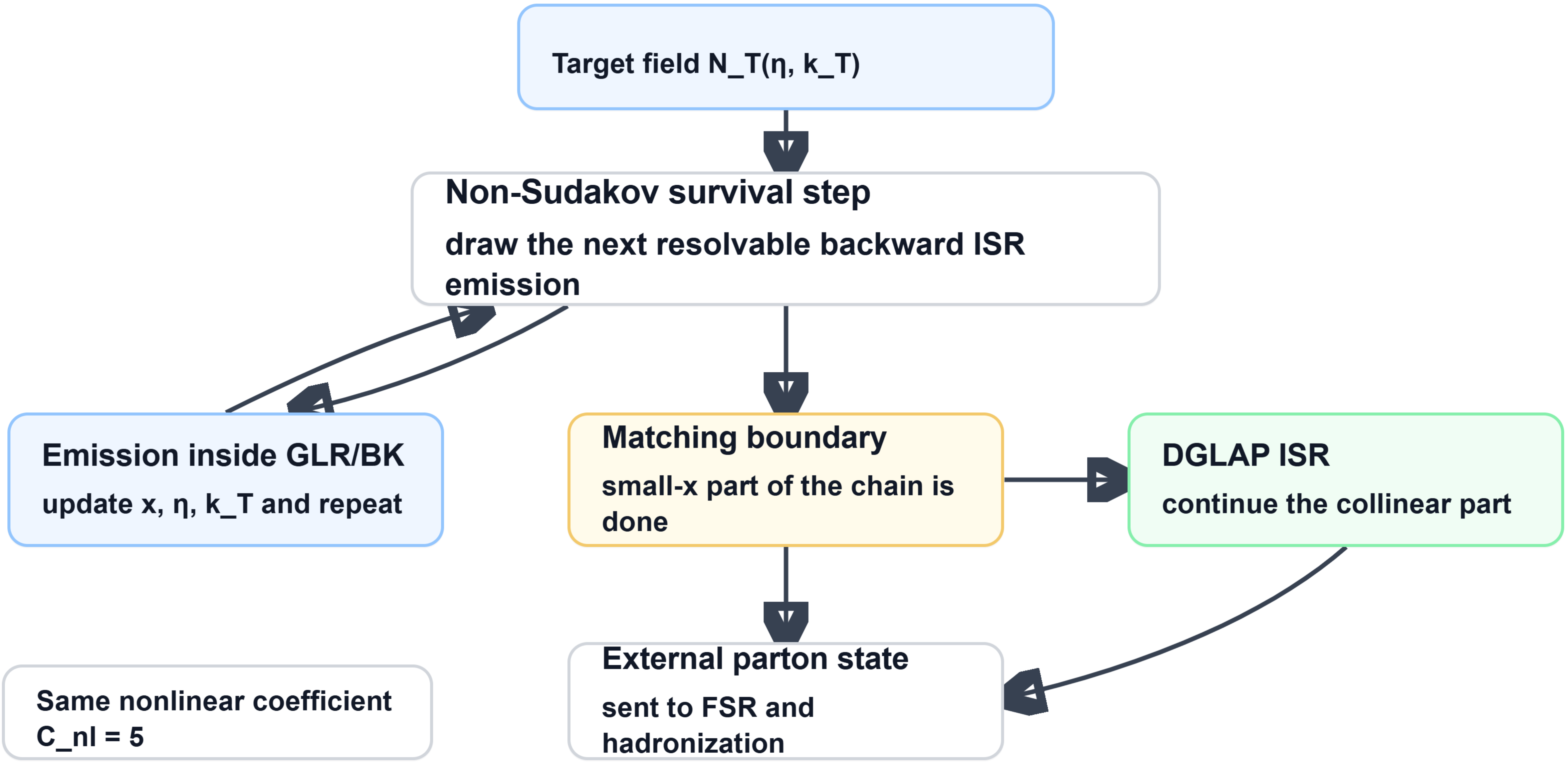
10.8亿	6967.8万	10 小时 5 ...	37 天	37 天
累计 Toke...	峰值 Toke...	最长任务...	当前连续...	最长连续...

Token 活动 每日 每周 累计

Architecture: target gluon field to hadronized event

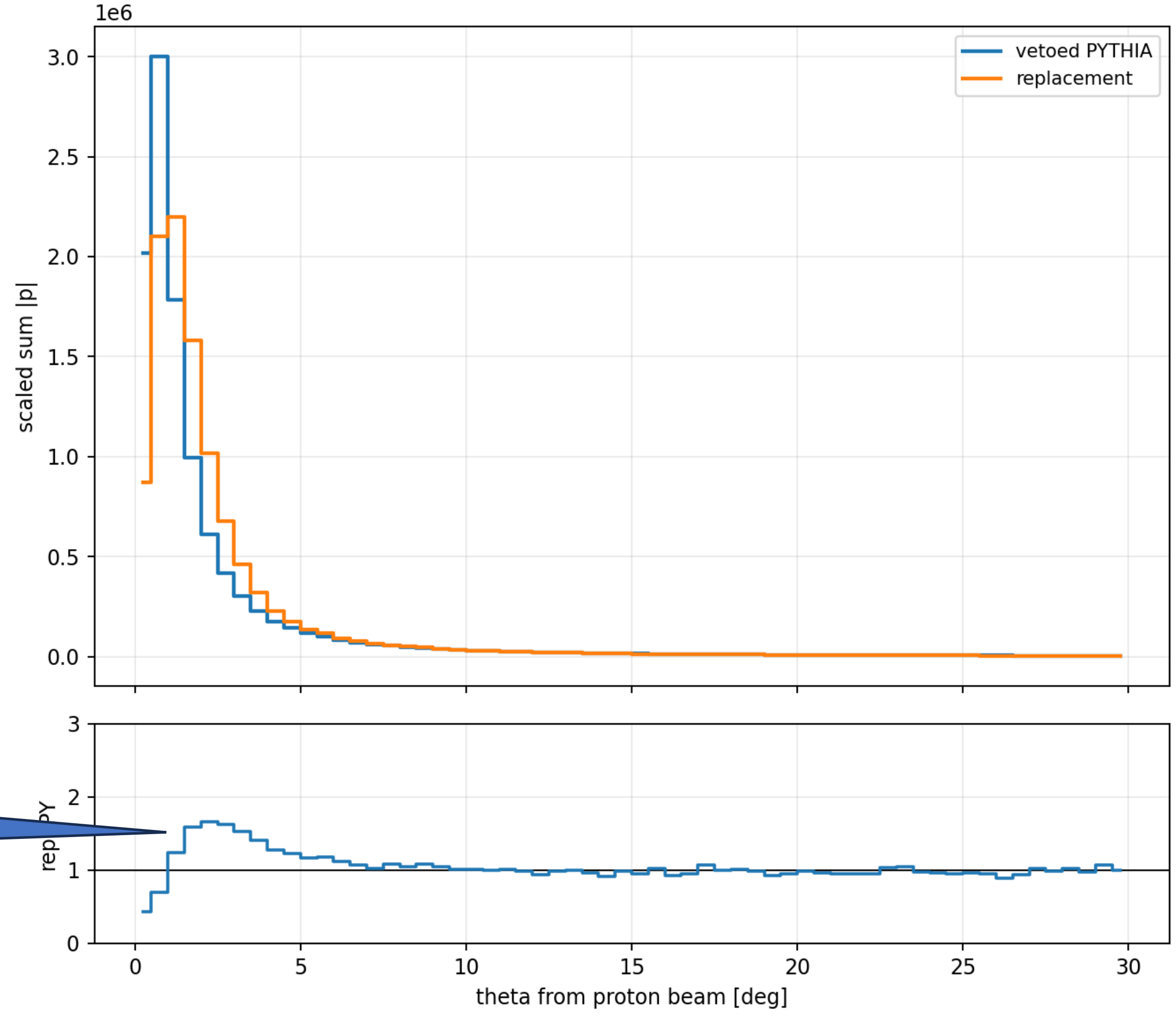


GLR/BK to DGLAP handoff



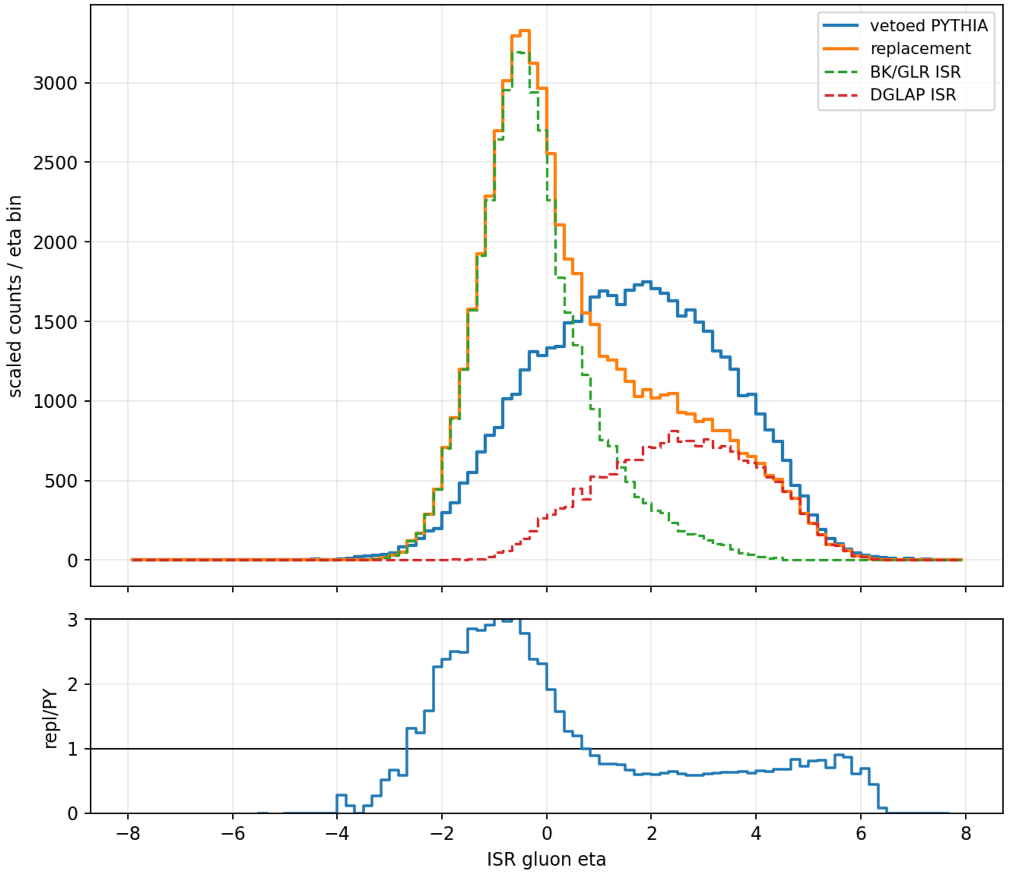
实验室系NEEC

Saturation 没有导致显著压低

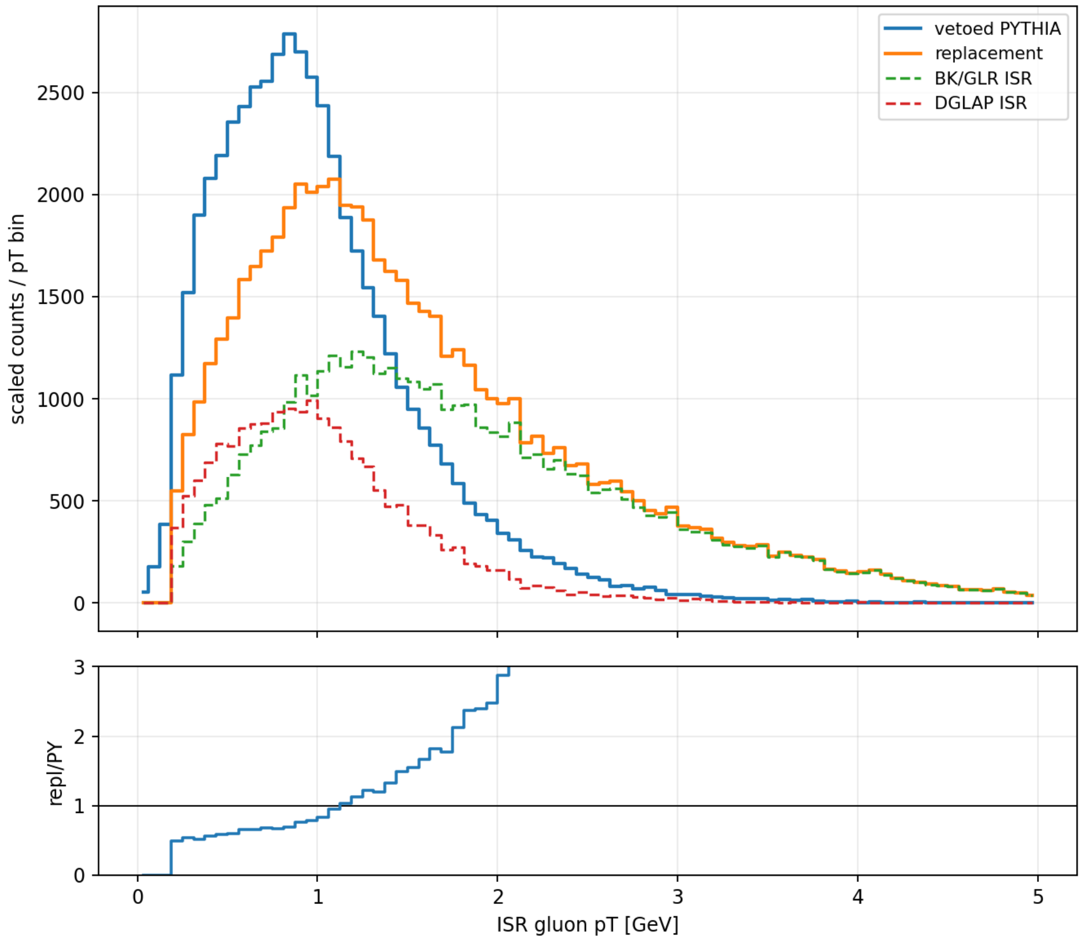


靶碎裂贡献

ISR对比图



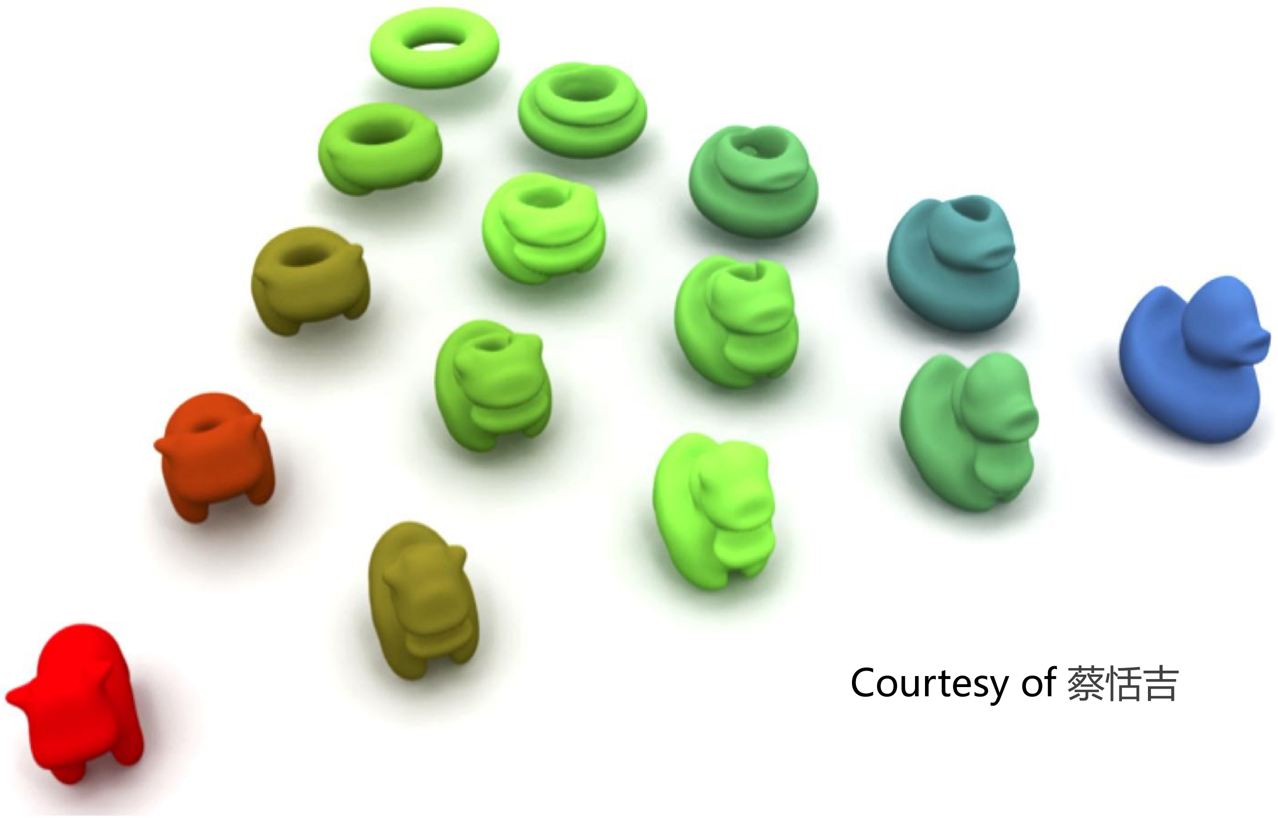
vetoed PYTHIA
replacement
BK/GLR ISR
DGLAP ISR
scaled counts / eta bin
3000
2500
2000
1500
1000
500
0
repl/PY
3
2
1
0
−8
−6
−4
−2
0
2
4
6
8
ISR gluon eta



vetoed PYTHIA
replacement
BK/GLR ISR
DGLAP ISR
scaled counts / pT bin
2500
2000
1500
1000
500
0
repl/PY
3
2
1
0
0
1
2
3
4
5
ISR gluon pT [GeV]

怎样更好的利用实验（PS）数据

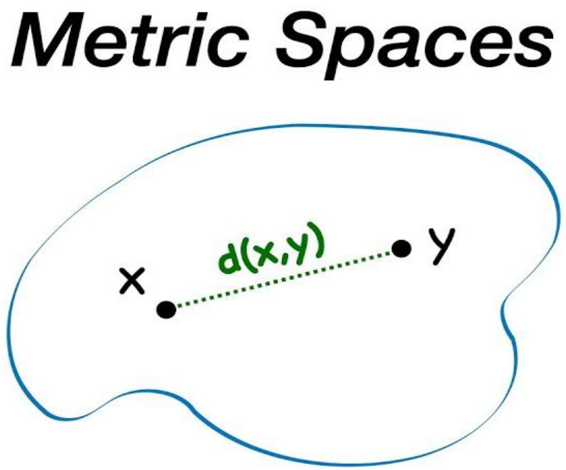
Optimal Transport(OT)， 充分利用所有实验数据。



Courtesy of 蔡恬吉

Transforming a cow into a donut or a duck…

怎样定义2次对撞事例形状的差距：



$$EMD(E,E') = \min_{f_{ij}\in\Gamma_{E,E'}} \sum_{ij} f_{ij}\theta_{ij}$$

红外安全，共线不敏感

Earth Mover's Distance (EMD): A First Example of OT

$$EMD(E,E') = \min_{f_{ij}\in\Gamma_{E,E'}} \sum_{ij} f_{ij}\theta_{ij}$$

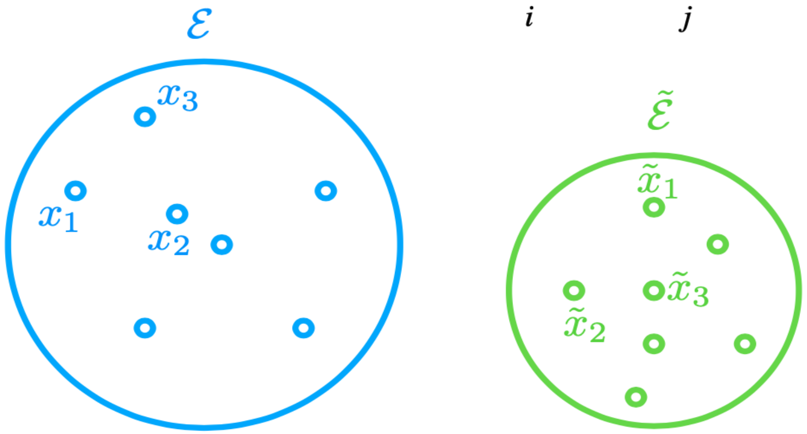
θ_{ij}: ground metric between particles i and j

f_{ij}: the amount of mass moved from particle i in E to particle j in E'.

Consider two "events" $\mathscr{E}$, $\tilde{\mathscr{E}}$

Collections of particles at locations $x_i, \tilde{x}_j$ in a rectangular domain with energies $E_i, \tilde{E}_j \geq 0$

Assume same total energy, $\sum_i E_i = \sum_j \tilde{E}_j$



The Metric Space of Collider Events

Patrick T. Komiske,[*] Eric M. Metodiev,[†] and Jesse Thaler[‡]

Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA and Department of Physics, Harvard University, Cambridge, MA 02138, USA

2019

When are two collider events similar? Despite the simplicity and generality of this question, there is no established notion of the distance between two events. To address this question, we develop a metric for the space of collider events based on the earth mover's distance: the "work" required to rearrange the radiation pattern of one event into another. We expose interesting connections between this metric and the structure of infrared- and collinear-safe observables, providing a novel technique to quantify event modifications due to hadronization, pileup, and detector effects. We showcase how this metrization unlocks powerful new tools for analyzing and visualizing collider data without relying upon a choice of observables. More broadly, this framework paves the way for data-driven collider phenomenology without specialized observables or machine learning models.

Courtesy of 蔡恬吉

Current numerical message: raw Sinkhorn only

Selection: x_g < 0.003, −2 < eta_lab < 0, full ISR + default FSR + hadronization.
The metric is applied directly to final-state flow maps.

Final-state object	Raw Sinkhorn choice	Z
charged hadrons	eta and log p_T flow map p_T-emphasis transport cost	**1.64**
anti-kT R=0.4 minijets	eta and log p_T flow map p_T-emphasis transport cost	**2.61**

Physics reading

the clearest signal is a shape difference of core transverse flow

Next step

freeze this raw definition before larger independent validation samples

Summary and Outlook

- The first PS algorithm incorporating saturation effect
- The implementation of the joint resummation is sketched

- Recoiled effect; linear polarization effect; multiple gluon fusion effect
- Figure out the strongest saturation signal from PS data
- Integrate into eHIJING

Thank you for your attention!

山东大学(青岛)
SHANDONG UNIVERSITY, QINGDAO