Comparisons of Predictions from Exact Amplitude-Based Resummation Methods with LHC and Cosmological Data

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Forward

** NEW PHYSICS/PRECISION ‘H’ AT LHC

Must Distinguish from Higher Order SM Processes AND Must Probe Precisely to Specify Uniquely

⇒ Precision QCD for the LHC

** UV LIMIT OF EINSTEIN’S THEORY

Can QFT Handle It?

⇒ Exact, Gauge Invariant Residual Control in Resummation for UV

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The Archetype:
*Approach to 1% Precision QCD for LHC Physics via MC Realized Amplitude-Based QED⊗QCD Resummation --

$$d\sigma = \sum_{i,j}\int dx_1 dx_2 F_i(x_1)F_j(x_2)d\hat{\sigma}_{res}$$

$$\Rightarrow \Delta\sigma_{th} = \Delta F \oplus \Delta\hat{\sigma}_{res} = \Delta\sigma_{th}(tech) \oplus \Delta\sigma_{th}(phys)$$

$$\Rightarrow$$

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$$d\hat{\sigma}_{res} = \sum_n d\hat{\sigma}_n$$

$$= e^{SUM_{IR}(QCED)} \sum_{m,n=0}^{\infty} \frac{1}{m!n!} \int \prod_{j_1=1}^{m} \frac{d^3 k_{j_1}}{k_{j_1}} \prod_{j_2=1}^{n} \frac{d^3 k_{j_2}}{k_{j_2}} \int \frac{d^4 y}{(2\pi)^4} e^{iy(p_1+q_1-p_2-q_2-\sum_{j1} k_{j1} - \sum_{j2} k'_{j2}) + D_{QCED}}$$

$$* \tilde{\tilde{\beta}}_{m,n}(k_1,\ldots,k_m;k'_1,\ldots,k'_n) \frac{d^3 p_2}{p_2^0} \frac{d^3 q_2}{q_2^0} \qquad (1)$$

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The Archetype:

*Approach to Feynman's Formulation of Einstein's Theory : Amplitude-Based Resummation of the Feynman Propagators therein

$$i\Delta'_F(k) = \frac{i}{k^2 - m^2 - \Sigma_s(k) + i\varepsilon}$$

$$= \frac{ie^{B''_g(k)}}{k^2 - m^2 - \Sigma'_s(k) + i\varepsilon}$$

$$\equiv i\Delta'_F(k)\big|_{\mathrm{Re}\,summed}$$

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Precision QCD for the LHC

- **Contact with Standard Resummations, SCT, SCET -- see Phys. Rev. D81(2010)076008**

Observations:

- EXACT – Compare:

  Sterman-Catani-Trentadue Threshold Resummation

  As for any f(z),

$$\left|\int_0^1 dz\, z^{n-1} f(z)\right| \le \left(\frac{1}{n}\right) max\left|f(z)\right|,$$

  drop non-singular contributions to cross section at z→1

- SCET:

  drop O(λ) terms, λ = √(Λ/Q),

  Λ∿ .3 GeV, Q∿100 GeV ⇒ λ≃5.5%

- These methods give approximations to our $\bar{\beta}_{n,m}$

Precision QCD for the LHC

- **Contact with Standard Resummations, CSS– RESBOS, etc.: (see 1305.0023 for details)**

$$\frac{d\sigma}{dQ^2 dy dQ_T^2} \sim \frac{4\pi^2\alpha^2}{9Q^2 s}\left\{ \int \frac{d^2b}{(2\pi)^2} e^{i\vec{Q}_T\cdot\vec{b}} \sum_j e_j^2 \widetilde{W}_j(b^*;Q,x_A,x_B) e^{\{-\ln(Q^2/Q_0^2)g_1(b)-g_{j/A}(x_A,b)-g_{j/B}(x_B,b)\}} + Y(Q_T;Q,x_A,x_B) \right\}$$

Dropped terms $O(Q_T/Q)$ in all orders of α_s :

at 5GeV, Q=M_Z, 5.5% Physical Precision Error(PPE)

Errors on the NP functions g_l also yield ~1.5% PPE,…

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- **Shower/ME Matching:**

Remove double counting between

$$\tilde{\bar{\beta}}_{m,n} \rightarrow \hat{\tilde{\bar{\beta}}}_{m,n}, \ \text{shower - subtracted residuals}$$

$$e^{SUM_{IR}}, e^{D}, F_1(x_1)F_2(x_2)\,|_{Shower\,Realization}$$

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- **IR-Improved DGLAP-CS Theory(PRD81(2010)076008):** **New resummed scheme for P_{AB}, reduced cross section derived from (1) applied to splitting process --**

$$\mathrm{F_j}, \hat{\sigma} \rightarrow \mathrm{F_j'}, \hat{\sigma}' \quad \text{for}$$

$$\mathrm{P_{qq}} \rightarrow \mathrm{P_{qq}^{exp}} = \mathrm{C_F} F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+z^2}{1-z}(1-z)^{\gamma_q}, \text{etc.},$$

giving the same value for σ, with improved MC stability

-- no need for IR cut-off (k_0) parameter

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- **Complete Set (γ_A are $O(\hbar)$) :**

$$P_{qq}^{exp}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \left[\frac{1+z^2}{1-z}(1-z)^{\gamma_q} - f_q(\gamma_q)\delta(1-z)\right],$$

$$P_{Gq}^{exp}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+(1-z)^2}{z} z^{\gamma_q},$$

$$P_{GG}^{exp}(z) = 2C_G F_{YFS}(\gamma_G) e^{\frac{1}{2}\delta_G} \{\frac{1-z}{z} z^{\gamma_G} + \frac{z}{1-z}(1-z)^{\gamma_G}$$
$$+ \frac{1}{2}(z^{1+\gamma_G}(1-z) + z(1-z)^{1+\gamma_G}) - f_G(\gamma_G)\delta(1-z)\},$$

$$P_{qG}^{exp}(z) = F_{YFS}(\gamma_G) e^{\frac{1}{2}\delta_G} \frac{1}{2}\{z^2(1-z)^{\gamma_G} + (1-z)^2 z^{\gamma_G}\},$$

$$\gamma_q = C_F \frac{\alpha_s}{\pi} t = \frac{4C_F}{\beta_0}, \qquad \delta_q = \frac{\gamma_q}{2} + \frac{\alpha_s C_F}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}),$$

$$f_q(\gamma_q) = \frac{2}{\gamma_q} - \frac{2}{\gamma_q+1} + \frac{1}{\gamma_q+2},$$

$$\gamma_G = C_G \frac{\alpha_s}{\pi} t = \frac{4C_G}{\beta_0}, \qquad \delta_G = \frac{\gamma_G}{2} + \frac{\alpha_s C_G}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}),$$

$$f_G(\gamma_G) = \frac{n_f}{6C_G F_{YFS}(\gamma_G)} e^{-\frac{1}{2}\delta_G} + \frac{2}{\gamma_G(1+\gamma_G)(2+\gamma_G)} + \frac{1}{(1+\gamma_G)(2+\gamma_G)}$$
$$+ \frac{1}{2(3+\gamma_G)(4+\gamma_G)} + \frac{1}{(2+\gamma_G)(3+\gamma_G)(4+\gamma_G)},$$

$$F_{YFS}(\gamma) = \frac{e^{-C\gamma}}{\Gamma(1+\gamma)}, \qquad C = 0.57721566...,$$

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- KEY PART OF APPROACH: BUILD ON EXISTING PLATFORMS

$\Longrightarrow$

IR-Improved DGLAP-CS Theory

$\cup$

NLO Parton Shower MC's: MC@NLO, POWHEG, …

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- Illustration:

$$d\sigma_{MC@NLO} = \left[B + V + \int (R_{MC} - C) d\Phi_R\right] d\Phi_B [\Delta_{MC}(0) + \int (R_{MC}/B)\Delta_{MC}(k_T) d\Phi_R]$$
$$+ (R - R_{MC})\Delta_{MC}(k_T) d\Phi_B d\Phi_R$$

$\Longrightarrow$ Sudakov FF

$$\Delta_{MC}(p_T) = e^{[-\int d\Phi_R \frac{R_{MC}(\Phi_B,\Phi_R)}{B}\theta(k_T(\Phi_B,\Phi_R)-p_T)]}$$

$\Longrightarrow$

$$\frac{1}{2}\hat{\bar{\bar{\beta}}}_{0,0} = \bar{B} + (\bar{B}/\Delta_{MC}(0)) \int (R_{MC}/B)\Delta_{MC}(k_T) d\Phi_R$$
$$\frac{1}{2}\hat{\bar{\bar{\beta}}}_{1,0} = R - R_{MC} - B\tilde{S}_{QCD}$$

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$$\bar{B} = B(1 - 2\alpha_s \Re B_{QCD}) + V + \int (R_{MC} - C) d\Phi_R$$

- **Rigorous Contact with Wilson's OPE:**
  Repeat the Gross-Wilczek-Politzer analysis of DIS.
  From

$$W^F_{\alpha\beta}(p_F,q)=\frac{1}{2\pi}\int d^4y\, e^{iqy}\langle p_F|[J_\beta(y),J_\alpha(0)]|p_F\rangle$$

$$=(2\pi)^3\sum_X \delta(q+p_F-p_X)\langle p_F|J_\beta(0)|p_X\rangle\langle p_X|J_\alpha(0)|p_F\rangle$$

(1) allows us to note that

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$$\langle p_X|J_\alpha(0)|p_F\rangle = e^{\alpha_s B_{QCD}} \langle p_X|J_\alpha(0)|p_F\rangle_{\text{IRI-virt}} \quad \Rightarrow$$

$$W^F_{\alpha\beta}(p_F,q) = (2\pi)^3 \sum_X \delta(q+p_F-p_X)\, e^{2\alpha_s \Re B_{QCD}} \;{}_{\text{IRI-virt}}\langle p_F|J_\beta(0)|p_X\rangle \langle p_X|J_\alpha(0)|p_F\rangle_{\text{IRI-virt}} \quad \Rightarrow$$

$${}_{\text{IRI-virt}}\langle p_F|J_\beta(0)|p_X\rangle \langle p_X|J_\alpha(0)|p_F\rangle_{\text{IRI-virt}}$$

$$= \tilde{S}_{QCD}(k_1)\cdots\tilde{S}_{QCD}(k_n)\; {}_{\text{IRI-virt}}\langle p_F|J_\beta(0)|p_{X'}\rangle \langle p_{X'}|J_\alpha(0)|p_F\rangle_{\text{IRI-virt}} + \cdots +$$

$${}_{\text{IRI-virt\&real}}\langle p_F|J_\beta(0)|p_{X'},k_1,\cdots,k_n\rangle \langle p_{X'},k_1,\cdots,k_n|J_\alpha(0)|p_F\rangle_{\text{IRI-virt\&real}}$$

$$\Rightarrow$$

$$W^F_{\beta\alpha}(p_F,q)=(2\pi)^3\sum_X \delta(q+p_F-p_X)e^{2\alpha_s \Re B_{QCD}}\Big[\tilde{S}_{QCD}(k_1)\cdots\tilde{S}_{QCD}(k_n)$$

$$_{\text{IRI-virt}}\langle p_F|J_\beta(0)|p_{X'}\rangle\langle p_{X'}|J_\alpha(0)|p_F\rangle_{\text{IRI-virt}}+\cdots$$

$$+\ _{\text{IRI-virt\&real}}\langle p_F|J_\beta(0)|p_{X'},k_1,\cdots,k_n\rangle\langle p_{X'},k_1,\cdots,k_n|J_\alpha(0)|p_F\rangle_{\text{IRI-virt\&real}}\Big]$$

$$=\frac{1}{2\pi}\int d^4y\sum_{X'}\sum_n\frac{1}{n!}\int\prod_{j=1}^n\frac{d^3k_j}{k_j^0}e^{\text{SUM}_{\text{IR}}(\text{QCD})}e^{iy(q+p_F-p_{X'}-\sum_j k_j)+D_{\text{QCD}}}$$

$$_{\text{IRI-virt\&real}}\langle p_F|J_\beta(0)|p_{X'},k_1,\cdots,k_n\rangle\langle p_{X'},k_1,\cdots,k_n|J_\alpha(0)|p_F\rangle_{\text{IRI-virt\&real}}$$

$$=\frac{1}{2\pi}\int d^4y\,e^{iqy}e^{\text{SUM}_{\text{IR}}(\text{QCD})+D_{\text{QCD}}}\ _{\text{IRI-virt\&real}}\langle p_F|[J_\beta(y),J_\alpha(0)]|p_F\rangle_{\text{IRI-virt\&real}},$$

$$\text{SUM}_{\text{IR}}(\text{QCD})=2\alpha_s\Re B_{\text{QCD}}+2\alpha_s\tilde{B}_{\text{QCD}}(\text{Kmax}),\quad 2\alpha_s\tilde{B}_{\text{QCD}}(\text{Kmax})=\int^{\le\text{Kmax}}\frac{d^3k}{k^0}\tilde{S}_{\text{QCD}}(k),$$

$$D_{\text{QCD}}=\frac{\int d^3k}{k}\tilde{S}_{\text{QCD}}(k)\left[e^{-iy\cdot k}-\theta(\text{Kmax}-k)\right]$$

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We use

$$W_{\beta\alpha}=\sum_a \int_0^1 \frac{dx}{x} F_a(x)\, W^a_{\beta\alpha}$$

to get

$$\int_0^1 dx\, x^n F_1(x,q^2)=\sum_j \tilde{\bar{C}}^{(n+1)}_{j,1}(q^2)\,\tilde{M}^{n+1}_j,$$

$$\int_0^1 dx\, x^n F_2(x,q^2)=\sum_j \tilde{\bar{C}}^{(n)}_{j,2}(q^2)\,\tilde{M}^{n+2}_j,$$

where

$$\tilde{\bar{C}}^{(n)}_{j,k}(q^2)=\frac{1}{2}i(q^2)^{n+1}\left(\frac{-\partial}{\partial q^2}\right)^n \int d^4y\, e^{iqy+\mathrm{SUM}_{\mathrm{IR}}(\mathrm{QCD})+D_{\mathrm{QCD}}}\frac{\tilde{\bar{C}}^{(n)}_{j,k}(y^2)}{y^2-i\epsilon y_0}$$

and

$$\langle p|\tilde{O}^j_{\mu_1\cdots\mu_n}(0)|p\rangle|_{\text{spin averaged}}\equiv$$

$$_{\text{IRI-virt\&real}}\langle p|O^j_{\mu_1\cdots\mu_n}(0)|p\rangle_{\text{IRI-virt\&real}}|_{\text{spin averaged}}=i^n\frac{1}{m_p}p_{p\mu_1}\cdots p_{p\mu_n}\tilde{M}^n_j+\cdots$$

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Still have Callan-Symanzik Eqn:

$$\left[\left(\mu\frac{\partial}{\partial\mu}+\beta(g)\frac{\partial}{\partial g}\right)\delta_{ij}-\tilde{\gamma}_{ij}^{(n)}(g)\right]\tilde{\tilde{C}}_{j,k}^{(n)}=0$$

for new matrix $\tilde{\gamma}_{ij}^{(n)}(g)$

We follow Curci, Furmanski and Petronzio(NPB175(1980)27):

For the NS operator ${}^{N}O^{F,b}(y)=\frac{1}{2}i^{N-1}S\bar{\psi}(y)\gamma_{\mu_1}\nabla_{\mu_2}\cdots\nabla_{\mu_N}\lambda^{b}\psi(y)-\text{trace terms},$

where $\nabla_{\mu}=\partial_{\mu}+ig\tau^{a}A_{\mu}^{a}$, S denotes symmetrization

$$\langle p|\ {}^{N}O^{F,b}(y)|p\rangle=\ {}^{F,b}O^{N}(\alpha_s,\epsilon)p_{\mu_1}\cdots p_{\mu_N}-\text{trace terms},\qquad {}^{F,b}O^{N}(\alpha_s,\epsilon)\equiv M_{F,b}^{N}\Rightarrow$$

$${}^{F,b}O^{N}(\alpha_s,\epsilon,p^2/\mu^2)=Z_O^{-1}(\alpha_s,\frac{1}{\epsilon})\ {}^{F,b}O_{\text{bare}}^{N}((\alpha_s)(\mu^2/p^2)^{\epsilon},\epsilon)$$

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Regulate collinear div. with $p^2 \neq 0$, $d=4-\varepsilon \Rightarrow$

- Use Δ, with $\Delta^2 = 0$,

$$ {}^{F,b}O^N(\alpha_s,\epsilon)=\langle p|\, {}^{N}O^{F,b}_{\mu_1\cdots\mu_N}(y)\,|p\rangle\,\Delta^{\mu_1}\cdots\Delta^{\mu_N}/(\Delta p)^N $$

Set $\Delta = n$, $x_{Bj} = np/np_p$, $x = nk/np$, $nA^a = 0 \Rightarrow$

$$ {}^{F,b}O^N(\alpha_s,\epsilon)=\int_{-1}^{1} dx\,x^{N-1}\ {}^{F,b}O(x,\alpha_s,\epsilon) $$

where

$$ {}^{F,b}O(x,\alpha_s,\epsilon)=Z_F[\delta(x-1)+x\frac{\int d^dk}{(2\pi)^d}\delta\left(x-\frac{kn}{pn}\right)\left[\frac{n}{4kn}T(p,k)p\right] $$

T(p,k) = fully connected 4-pt fn., Z_F = field renorm., and

[**b** B denotes $b_{\alpha\alpha'}$, $B^{\alpha\alpha'}{}_{\beta\beta'}$, etc.

Analytic continuation to d=4+ε, ε>0, $p^2\rightarrow 0$ gives (CFP)

$$Z_O^{-1}(\alpha_s,\frac{1}{\epsilon})=\int_{-1}^{1}dx\,x^{N-1}\left[\Gamma_{qq}(x,\alpha_s,\frac{1}{\epsilon})\theta(x)-\Gamma_{q\bar{q}}(-x,\alpha_s,\frac{1}{\epsilon})\theta(-x)\right]$$

$\Gamma_{qq}(\Gamma_{q\bar{q}})\Leftrightarrow$ respective parton density for a quark(anti-quark) in a quark $\Rightarrow$ coefficients of $\frac{1}{\epsilon}$ give

$$-\gamma^{(N)}(\alpha_s)=2\int_{-1}^{1}dx\,x^{N-1}\left[P_{qq}(x,\alpha_s)\theta(x)-P_{q\bar{q}}(-x,\alpha_s)\theta(-x)\right]$$

$$=2\left[P_{qq}(N,\alpha_s)+(-1)^N P_{q\bar{q}}(N,\alpha_s)\right],$$

$F(N)=\int_0^1 dx\,x^{N-1}F(x)$, and

$P_{BA}\Leftrightarrow$ usual DGLAP-CS kernels in CFP convention,

with $\gamma^{(N)}(\alpha_s)\Leftrightarrow$ anomalous dimension of ${}^{N}O^{F,b}$

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Appliication to new IR-improved anomalous dimension matrix:

We IR-improve each step –

$$\langle p|\ {}^{N}O^{F,b}(y)|p\rangle \Rightarrow \langle p|\ {}^{N}\tilde{O}^{F,b}(y)|p\rangle$$

and $\quad {}^{F,b}O^{N}(\alpha_s,\epsilon) \Rightarrow {}^{F,b}\tilde{O}^{N}(\alpha_s,\epsilon) \quad \Rightarrow$

$${}^{F,b}\tilde{O}^{N}(\alpha_s,\epsilon,p^2/\mu^2)=Z_{\tilde{O}}^{-1}(\alpha_s,\frac{1}{\epsilon})\ {}^{F,b}\tilde{O}^{N}_{bare}((\alpha_s)(\mu^2/p^2)^{\epsilon},\epsilon)\Rightarrow$$

$${}^{F,b}\tilde{O}^{N}(\alpha_s,\epsilon)=\int_{-1}^{1}dx\,x^{N-1}\ {}^{F,b}\tilde{O}(x,\alpha_s,\epsilon) \text{ where}$$

$${}^{F,b}\tilde{O}(x,\alpha_s,\epsilon)=Z_F[\delta(x-1)+x\frac{\int d^dk}{(2\pi)^d}\delta(x-\frac{kn}{pn})\left[\frac{n}{4kn}\tilde{T}(p,k)p\right]$$

$\tilde{T}(p,k)$ is IR-improved T(p,k) →

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IR-improved result:

$$Z_{\delta}^{-1}(\alpha_s,\frac{1}{\epsilon})=\int_{-1}^{1}dx\,x^{N-1}[\Gamma_{qq}^{exp}(x,\alpha_s,\frac{1}{\epsilon})\theta(x)-\Gamma_{q\bar{q}}^{exp}(-x,\alpha_s,\frac{1}{\epsilon})\theta(-x)]$$

where Γ_{qq}^{exp}, $\Gamma_{q\bar{q}}^{exp}$ are the respective IR-improved parton densities $\Rightarrow$

$$-\tilde{\gamma}_{\delta}^{(N)}(\alpha_s)=2\frac{\alpha_s}{2\pi}[P_{qq}^{exp}(N,\alpha_s)+(-1)^N P_{q\bar{q}}^{exp}(N,\alpha_s)]$$

where P_{qq}^{exp}, $P_{q\bar{q}}^{exp}$ $\Leftrightarrow$ respective IR-improved kernels $\Rightarrow$

IR-improved one-loop identifications

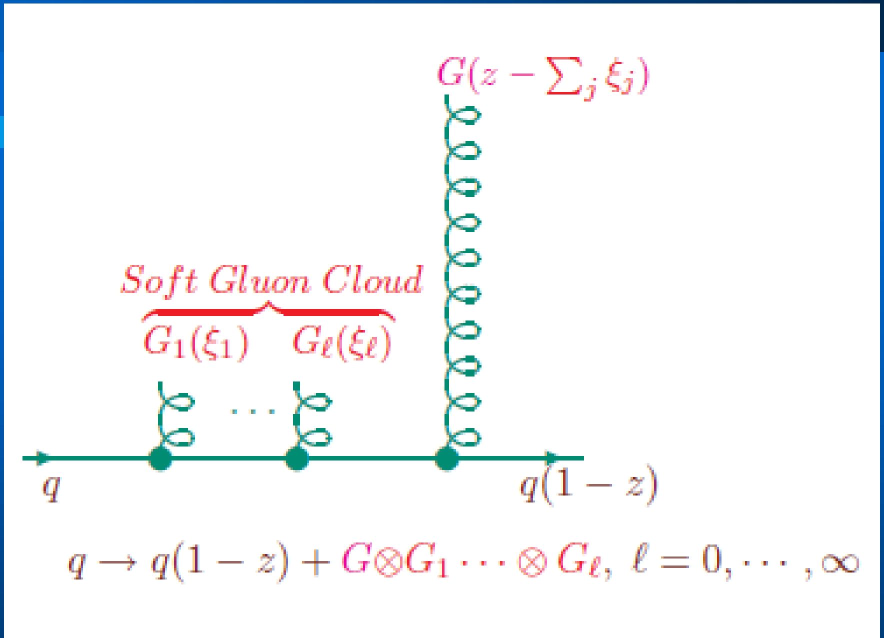
$$-\tilde{\gamma}^{(N)}(\alpha_s)_{ij}=2\frac{\alpha_s}{2\pi}P_{ij}^{exp}(N),$$

rigorous contact with new IR-improved DGLAP-CS theory

Basic Physical Idea:
Bloch-Nordsieck –

Accelerated Charge ⇒ Coherent State of Soft Gluons (Photons)

⇒ More Physical View of Splitting Process ($O(\hbar^n)$, n≥1, corrections):



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Basic Physical Idea:
Bloch-Nordsiek –

More Physical View of Splitting Process in Practice:

$$P_{AB}(z) \longrightarrow P^{exp}{}_{AB}(z)$$

Resum terms $O((\alpha_s \ln(q^2/\Lambda^2) \ln(1-z))^n)$
for IR limit $z \longrightarrow 1 \Rightarrow$
Generate Gribov-Lipatov exponents γ_A .

•Example Direct Calculation

$$\int \frac{\alpha_s(t)}{2\pi} P_{BA}\, dt\, dz = e^{\mathrm{SUM_{IR}(QCD)}(z)} \int \{ \bar{\bar{\beta}}_0 \int \frac{d^4y}{(2\pi)^4} e^{\{iy\cdot(p_1-p_2)+\int^{k<K_{max}} \frac{d^3k}{k} \tilde{S}_{\mathrm{QCD}}(k)\left[e^{-iy\cdot k}-1\right]\}}$$

$$+ \int \frac{d^3k_1}{k_1} \bar{\bar{\beta}}_1(k_1) \int \frac{d^4y}{(2\pi)^4} e^{\{iy\cdot(p_1-p_2-k_1)+\int^{k<K_{max}} \frac{d^3k}{k} \tilde{S}_{\mathrm{QCD}}(k)\left[e^{-iy\cdot k}-1\right]\}}$$

$$+ \cdots \} \frac{d^3p_2}{p_2^0} \frac{d^3q_2}{q_2^0}$$

$$= e^{\mathrm{SUM_{IR}(QCD)}(z)} \int \{ \bar{\bar{\beta}}_0 \int_{-\infty}^{\infty} \frac{dy}{(2\pi)} e^{\{iy\cdot(E_1-E_2)+\int^{k<K_{max}} \frac{d^3k}{k} \tilde{S}_{\mathrm{QCD}}(k)\left[e^{-iyk}-1\right]\}}$$

$$+ \int \frac{d^3k_1}{k_1} \bar{\bar{\beta}}_1(k_1) \int_{-\infty}^{\infty} \frac{dy}{(2\pi)} e^{\{iy\cdot(E_1-E_2-k_1^0)+\int^{k<K_{max}} \frac{d^3k}{k} \tilde{S}_{\mathrm{QCD}}(k)\left[e^{-iy\cdot k}-1\right]\}}$$

$$+ \cdots \} \frac{d^3p_2}{p_2^0 q_2^0}$$

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$$I_{YFS}(zE,0) = \int_{-\infty}^{\infty} \frac{dy}{2\pi} e^{[iy(zE)+\int^{k<zE} \frac{d^3k}{k}\tilde{S}_{QCD}(k)(e^{-iyk}-1)]}$$
$$= F_{YFS}(\gamma_q)\frac{\gamma_q}{zE}$$
$$I_{YFS}(zE,k_1) = \int_{-\infty}^{\infty} \frac{dy}{2\pi} e^{[iy(zE-k_1)+\int^{k<zE} \frac{d^3k}{k}\tilde{S}_{QCD}(k)(e^{-iyk}-1)]}$$
$$= (\frac{zE}{zE-k_1})^{1-\gamma_q} I_{YFS}(zE,0)$$

$$\int \left(\bar{\bar{\beta}}_0 \frac{\gamma_q}{zE} + \int dk_1 k_1 d\Omega_1 \bar{\bar{\beta}}_1(k_1)(\frac{zE}{zE-k_1})^{1-\gamma_q}\frac{\gamma_q}{zE}\right)\frac{d^3p_2}{E_2 q_2^0} = \int dt \frac{\alpha_s(t)}{2\pi} P^0_{BA} dz + \mathcal{O}(\alpha_s^2).$$

so that differentiation yields

$$P_{BA} = P^0_{BA} z^{\gamma_q} F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q}$$

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- Herwiri1.031(PRD81(2010)076008):

w consultation from Bryan Webber, Stefano Frixione, and Mike Seymour, implementation of IR-improved kernels in Herwig 6.5 environment to get Herwiri1.031, MC@NLO/Herwiri1.031.

Observations:

1. SUM_{IR} is an IR effect – It contains as designed only the IR part of the LL, the rest of the LL is in D and the residuals $\hat{\tilde{\bar{\beta}}}_m$, as we show in PRD81(2010)076008.
2. Herwiri is just as general as Herwig6.5, as they run the same set of processes

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- Herwiri++, Herwiri++/Powheg, Herwiri++/MC@NLO -- running but still undergoing check-out
- Pythia8(Tjorborn Sjostrand, Peter Skands) , in progress
- Sherpa(JanWinter), in progress

- Important Technical Point on MC@NLO vs POWHEG
Hardest Emission Sudakov in POWHEG uses full $O(\alpha_s)$ emission result (we follow 0803.0883)

$$\Delta_{\hat{R}}(p_T) = \exp\left[-\int d\Phi_R \frac{\hat{R}(\Phi_B, \Phi_R)}{B(\Phi_B)} \theta(k_T(\Phi_B, \Phi_R) - p_T)\right]$$

$\Rightarrow$ must synthesize this with (1) as well

- Some initial illustrative results follow first.

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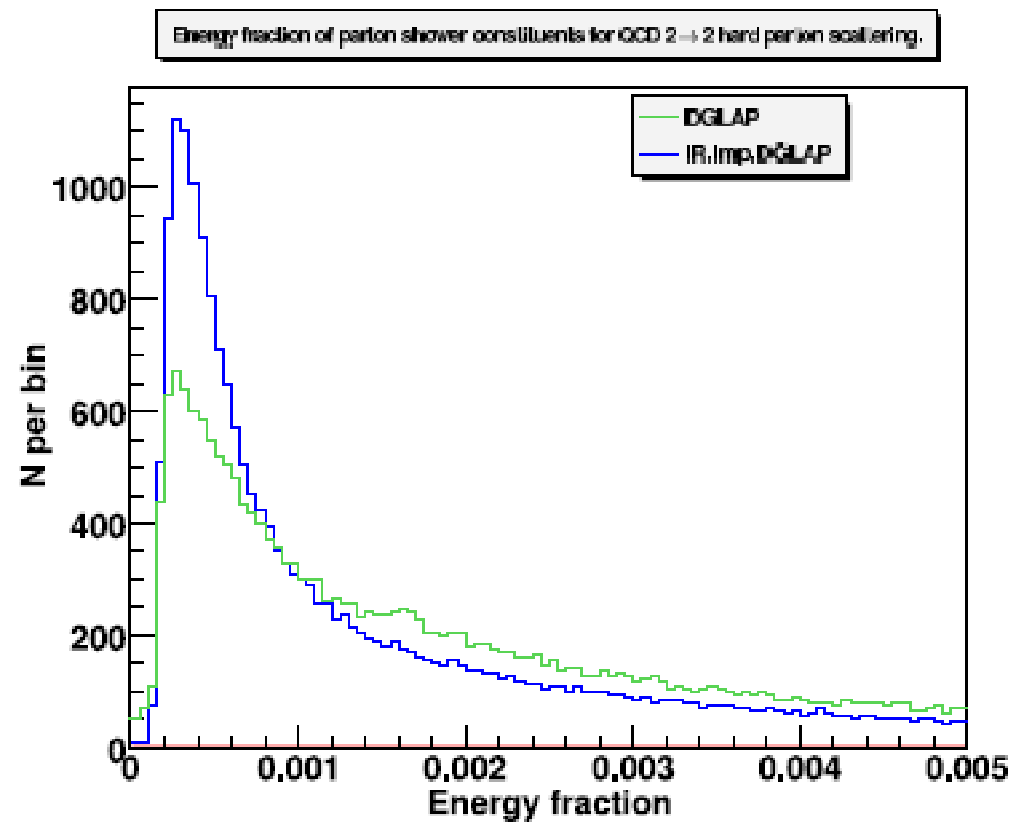

Figure 3: The z-distribution(ISR parton energy fraction) shower comparison in HERWIG6.5.

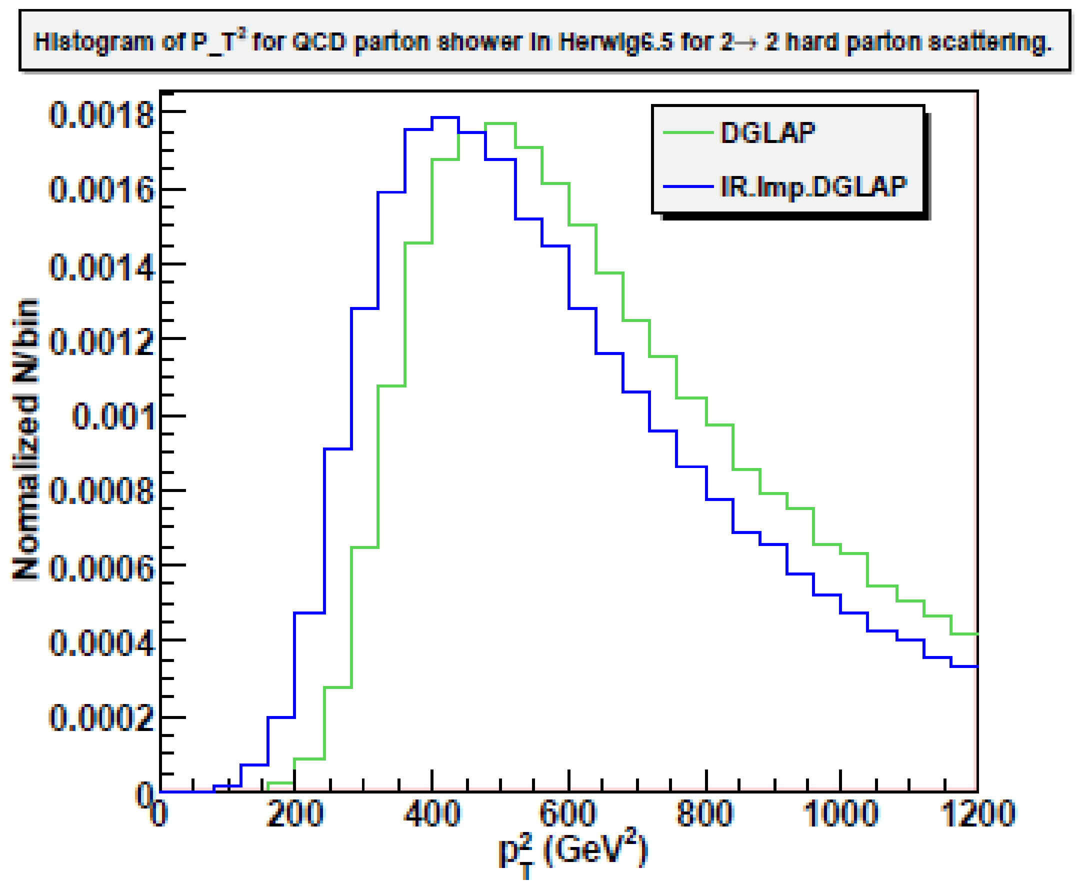

Figure 4: The p_T^2-distribution (ISR parton) shower comparison in HERWIG6.5.

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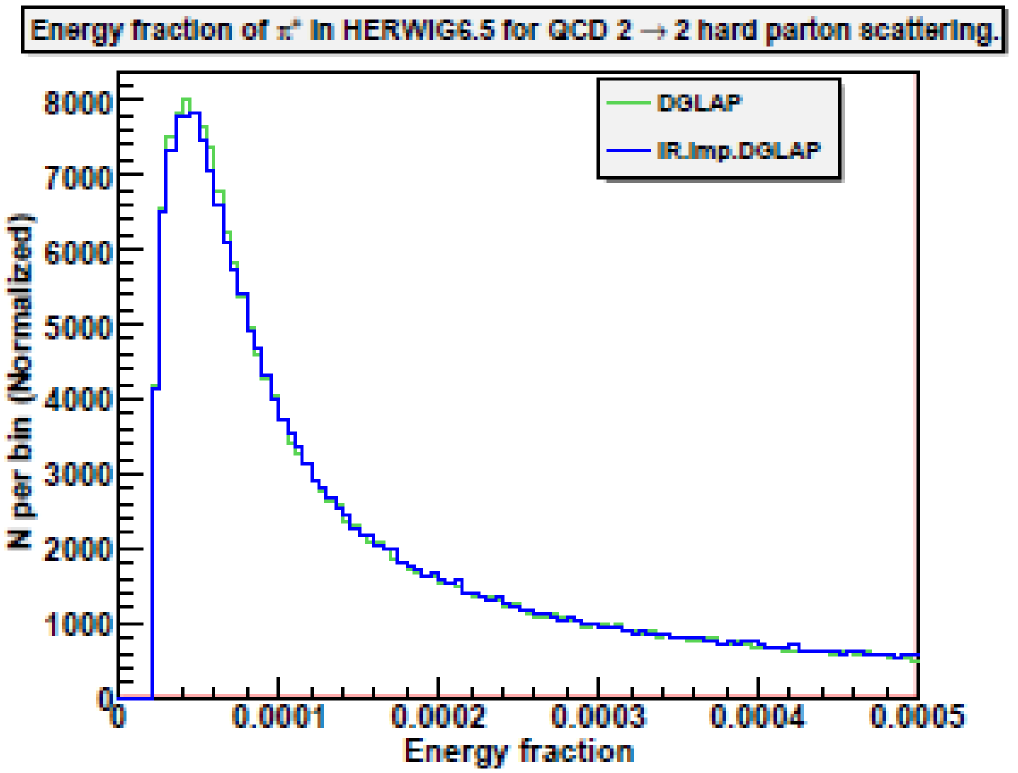

Figure 5: The π^+ energy fraction distribution shower comparison in HERWIG6.5.

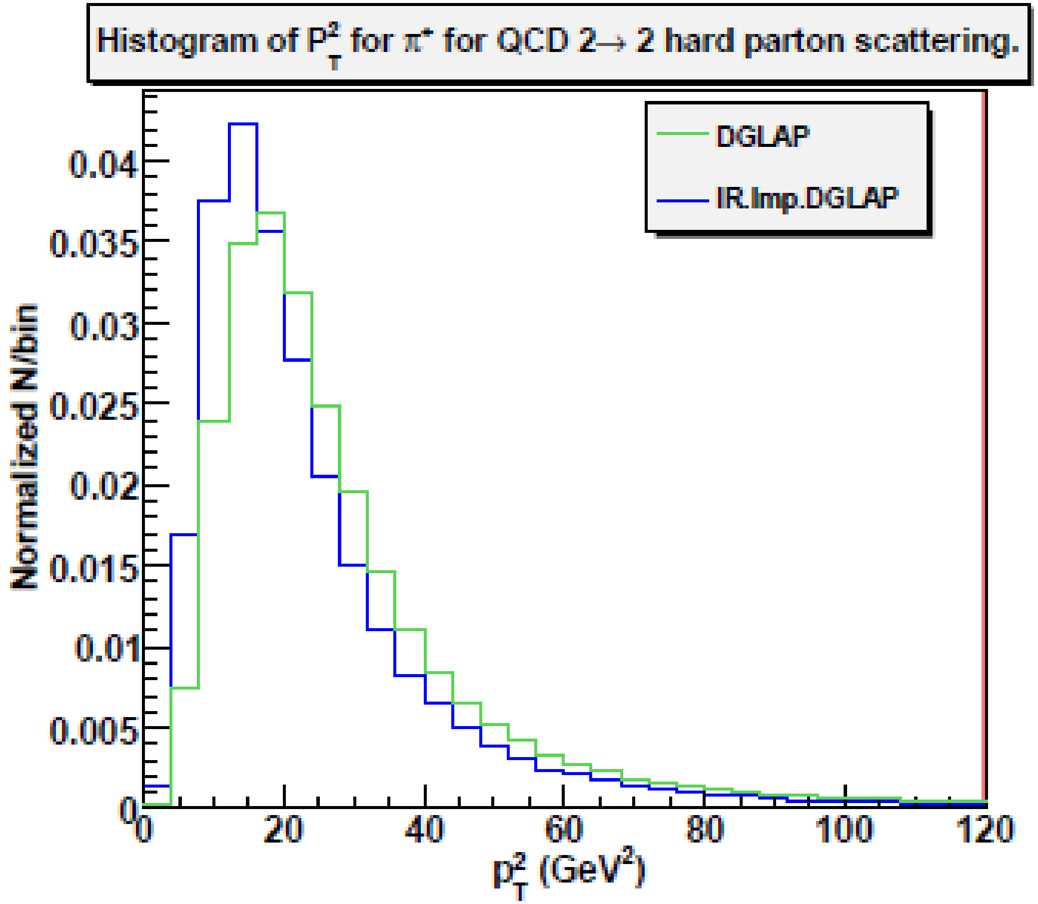

Figure 6: The π^+ p_T^2-distribution shower comparison in HERWIG6.5.

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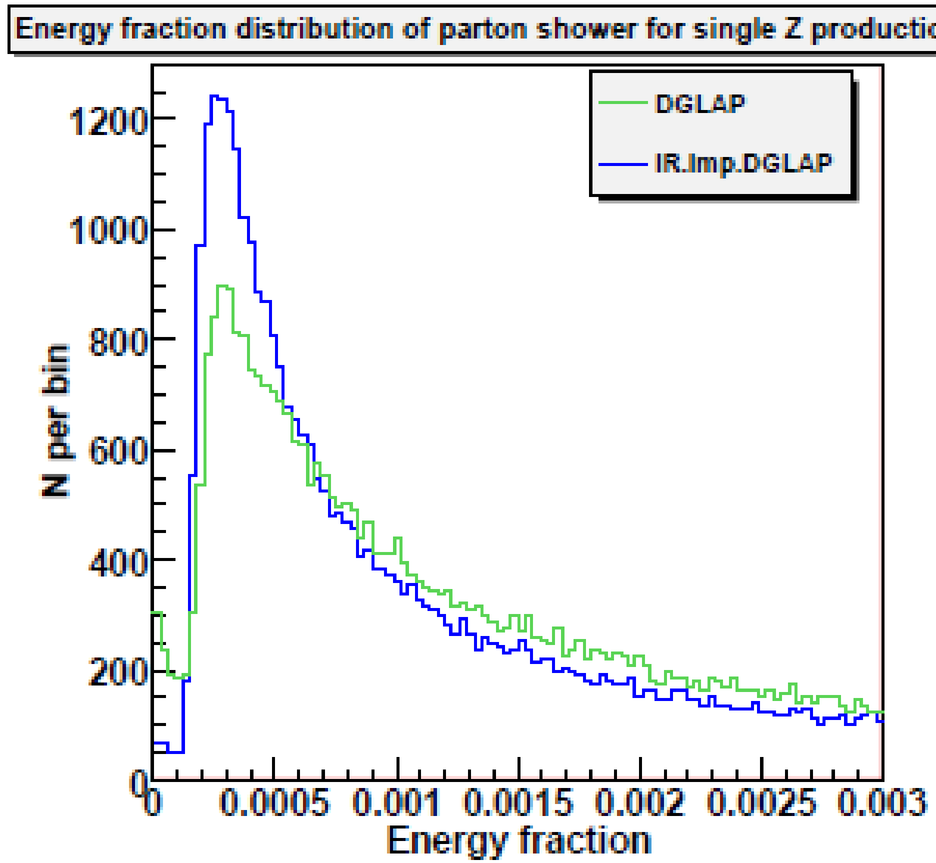

Figure 7: The z-distribution(ISR parton energy fraction) shower comparison in HERWIG6.5.

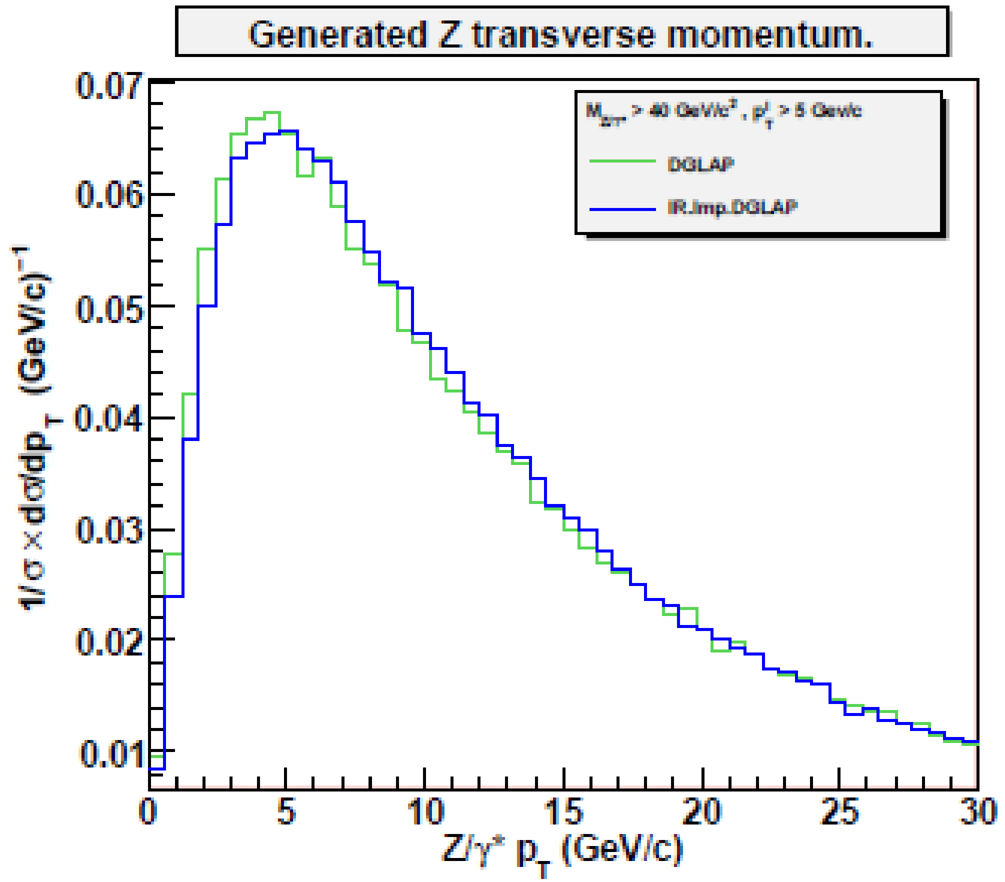

Figure 8: The Z p_T-distribution(ISR parton shower effect) comparison in HERWIG6.5.

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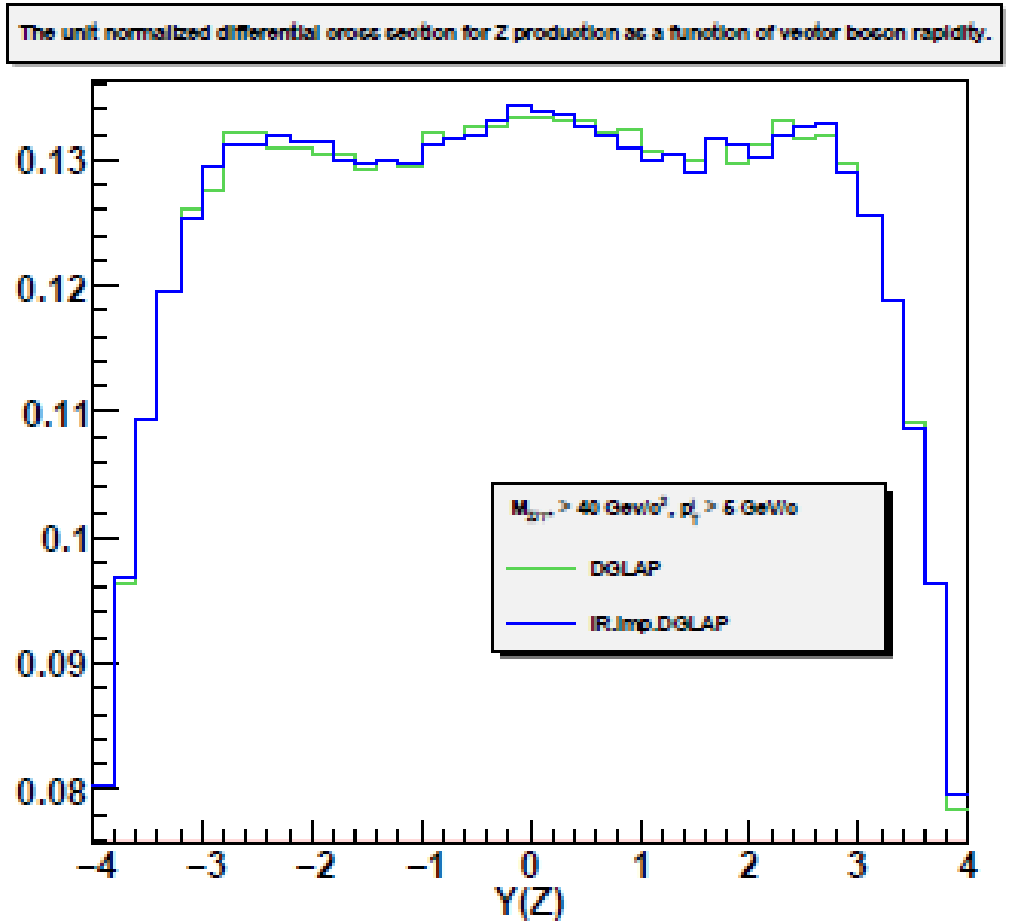

Figure 9: The Z rapidity-distribution(ISR parton shower) comparison in HERWIG6.5.

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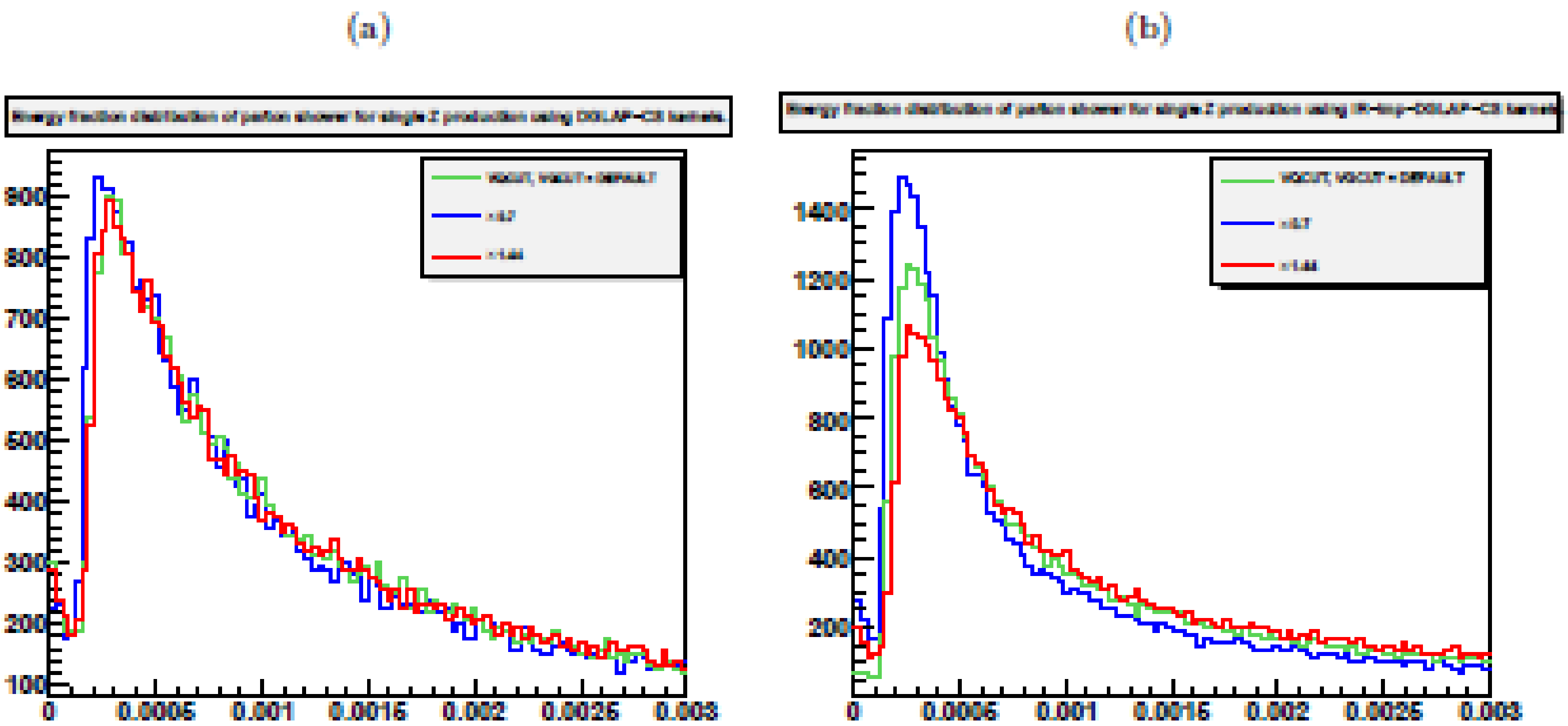

Figure 10: IR-cut-off sensitivity in z-distributions of the ISR parton energy fraction: (a), DGLAP-CS (b), IR-I DGLAP-CS – for the single Z hard sub-process in HERWIG-6.5 environment.

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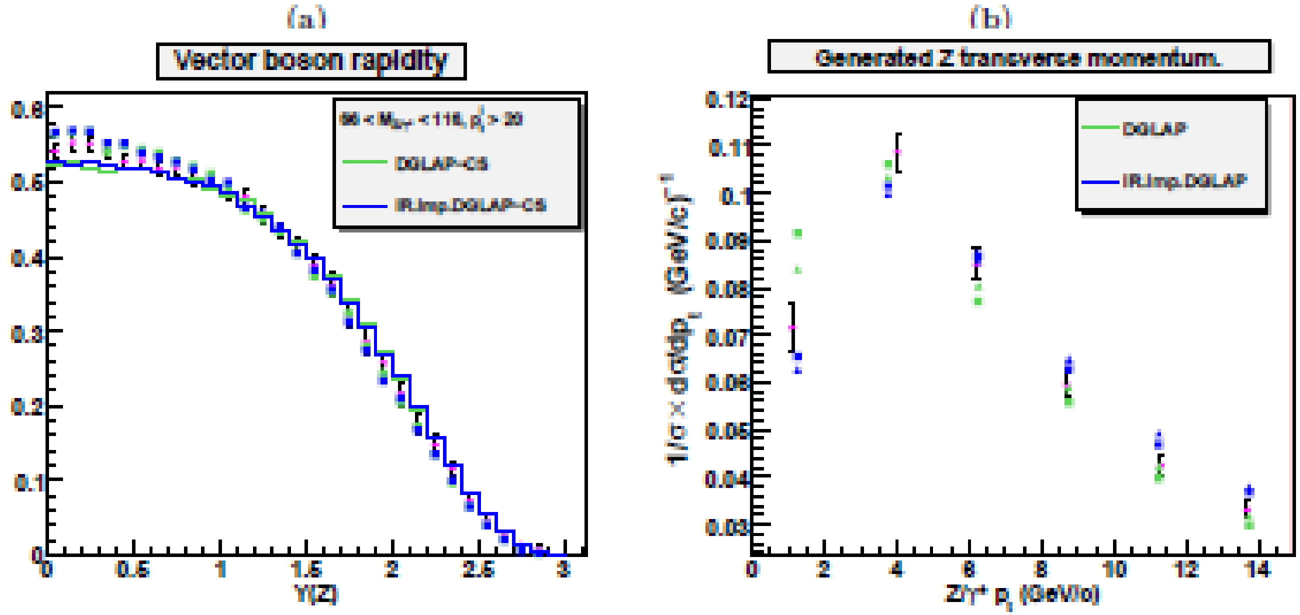

Figure 11: Comparison with FNAL data: (a), CDF rapidity data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data, the green(blue) lines are HERWIG6.510(HERWIRI1.031); (b), D0 p_T spectrum data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data, the blue triangles are HERWIRI1.031, the green triangles are HERWIG6.510. In both (a) and (b) the blue squares are MC@NLO/HERWIRI1.031, and the green squares are MC@NLO/HERWIG6.510, where we use the notation (see the text) MC@NLO/X to denote the realization by MC@NLO of the exact $\mathcal{O}(\alpha_s)$ correction for event generator X. Note that these are untuned theoretical results.

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- **HERWIRI1.031 -- PRD81 (2010) 076008:**
  - For the CDF rapidity data, HERWIRI1.031 is closer to the data than is HERWIG6.510 (1.54 vs 1.77 for χ^2/d.o.f. resp.);
    for MC@NLO/HERWIRI1.031 and MC@NLO/HERWIG6.510
    the χ^2/d.o.f are 1.42 and 1.40 resp., both are within 10% of the data
    $\Rightarrow$ Need NNLO level, in progress.
  - For the D0 p_T data, HERWIRI1.031 gives a better fit
    to the data compared to HERWIG6.5 for low p_T,
    for $p_T < 12.5$GeV, the χ^2/d.o.f. are $\sim$ 2.5 and 3.3 respectively
    - we add the statistical and systematic errors,
    showing that the IR-improvement makes a better representation
    of QCD in the soft regime for a given fixed order in perturbation theory.

• LHC DATA: CMS Rapidity & ATLAS PT Spectrum for Z/γ* Production

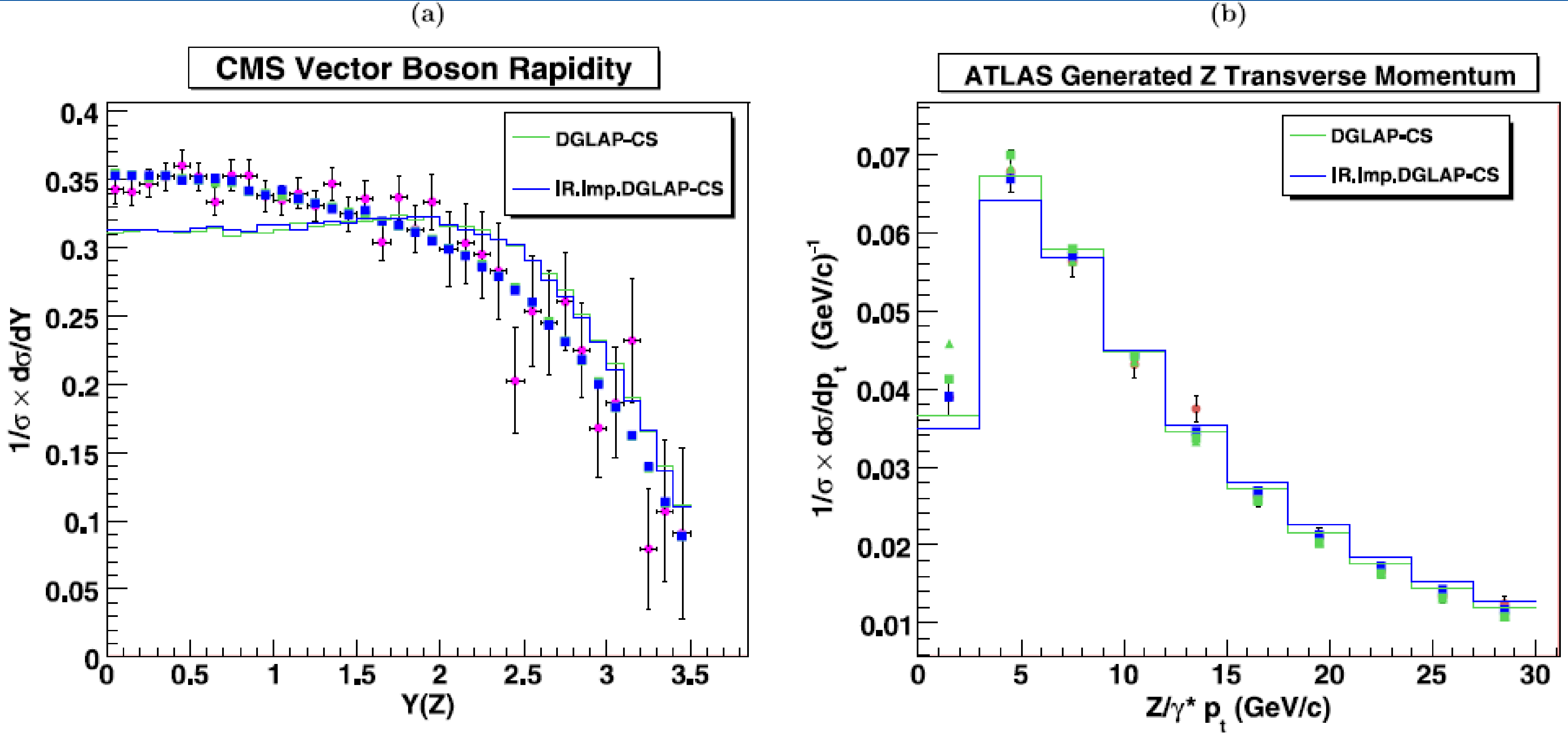

Fig. 2. Comparison with LHC data: (a) CMS rapidity data on (Z/γ^*) production to e^+e^-, $\mu^+\mu^-$ pairs, the circular dots are the data, the green (blue) lines are HERWIG6.510 (HERWIRI1.031); (b) ATLAS p_T spectrum data on (Z/γ^*) production to (bare) e^+e^- pairs, the circular dots are the data, the blue (green) lines are HERWIRI1.031 (HERWIG6.510). In both (a) and (b) the blue (green) squares are MC@NLO/HERWIRI1.031 (HERWIG6.510 (PTRMS = 2.2 GeV)). In (b), the green triangles are MC@NLO/HERWIG6.510 (PTRMS = 0). These are otherwise untuned theoretical results. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

• Observations

1. For the unimproved case, the data suggest that we need a GAUSSIAN (intrinsic) PTRMS ≅ 2.2 GeV [Herwiri1.031(blue line), Herwig6510(green line(PTRMS=2.2GeV)), MC@NLO/Herwiri1.031(blue squares), MC@NLO/Herwig6510(green squares (PTRMS=2.2GeV), green triangles(PTRMS=0))] (similar to what holds at FNAL)
2. This same shape is provided from fundamental principles by the MC@NLO/Herwiri1.031 with PTRMS ≅ 0 GeV (similar to what holds at FNAL)

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• Observations (Quantitative)

1. Unimproved case, the respective χ^2 /d.o.f.'s are 1.37, 0.70 (MC@NLO/Herwig6510(PTRMS=2.2GeV)) for the p_T and rapidity data
2. IR-improved case, the respective χ^2 /d.o.f.'s are 0.72, 0.72 (MC@NLO/Herwiri1.031) for the p_T and rapidity data
3. Unimproved case, the respective χ^2 /d.o.f.'s are 2.23, 0.70 (MC@NLO/Herwig6510(PTRMS=0)) for the p_T and rapidity data

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• Which is Better for Precision QCD Theory?

1. Precocious Bjorken Scaling in SLAC-MIT Experiments: already at $Q^2 \cong 1_+ \text{ GeV}^2$

$\Rightarrow$ PTRMS^2 small compared to 1_+ GeV^2

See R.P. Feynman, M. Kislinger and F. Ravndal, Phys. Rev. D**3** (1971) 2706; R. Lipes, *ibid.***5** (1972) 2849; F.K. Diakonas, N.K. Kaplis and X.N. Mawita, *ibid.* **78** (2008) 054023; K. Johnson, Proc. Scottish Summer School Phys. **17** (1976) p. 245; A. Chodos *et al.*, Phys. Rev. D**9** (1974) 3471; *ibid.* **10** (1974) 2599; T. DeGrand *et al.*, *ibid.* **12** (1975) 2060; …. – all have $\text{PTRMS}^2 << 1_+ \text{ GeV}^2$

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- Which is Better for Precision QCD Theory?

2. The first principles approach is not subject to arbitrary functional variation to determine its $\Delta\sigma_{\rm th}$
3. Experimentally, in principle, events in the two cases should look different in terms of the properties of the rest of the particles in the events – this is under study.

Here, we show the following.

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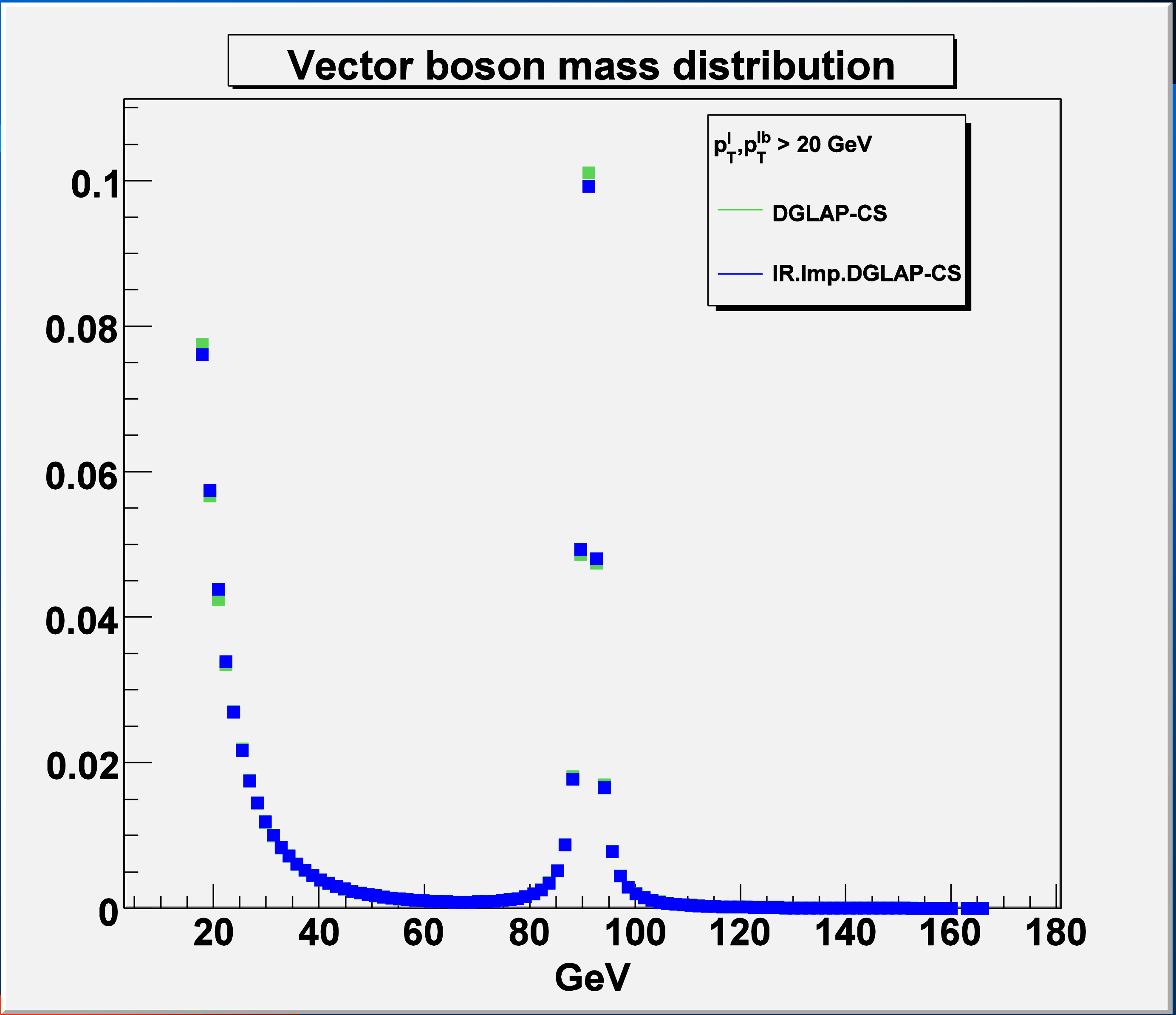
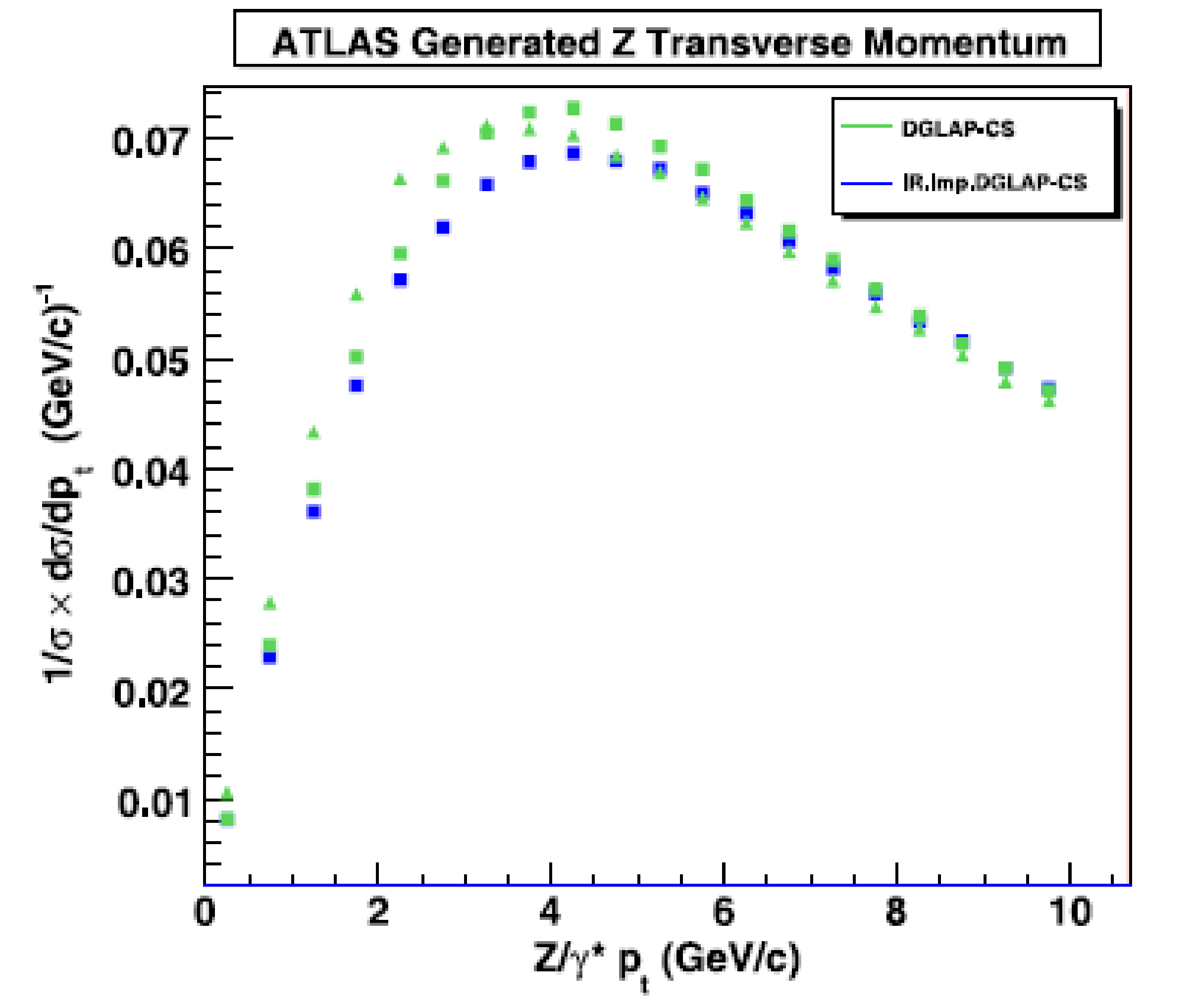
For example: 2.2% Peak Effect



THEORY COMPARISON: FINER BINS -- 0.5GeV vs 3.0GeV



OBSERVATIONS

* IR-Improved DGLAP-CS Theory Increases Definiteness of Precision Determination of NLO Parton Shower MC's and Improves Such.
* More Potential Checks Against Experiment Are Being Pursued.

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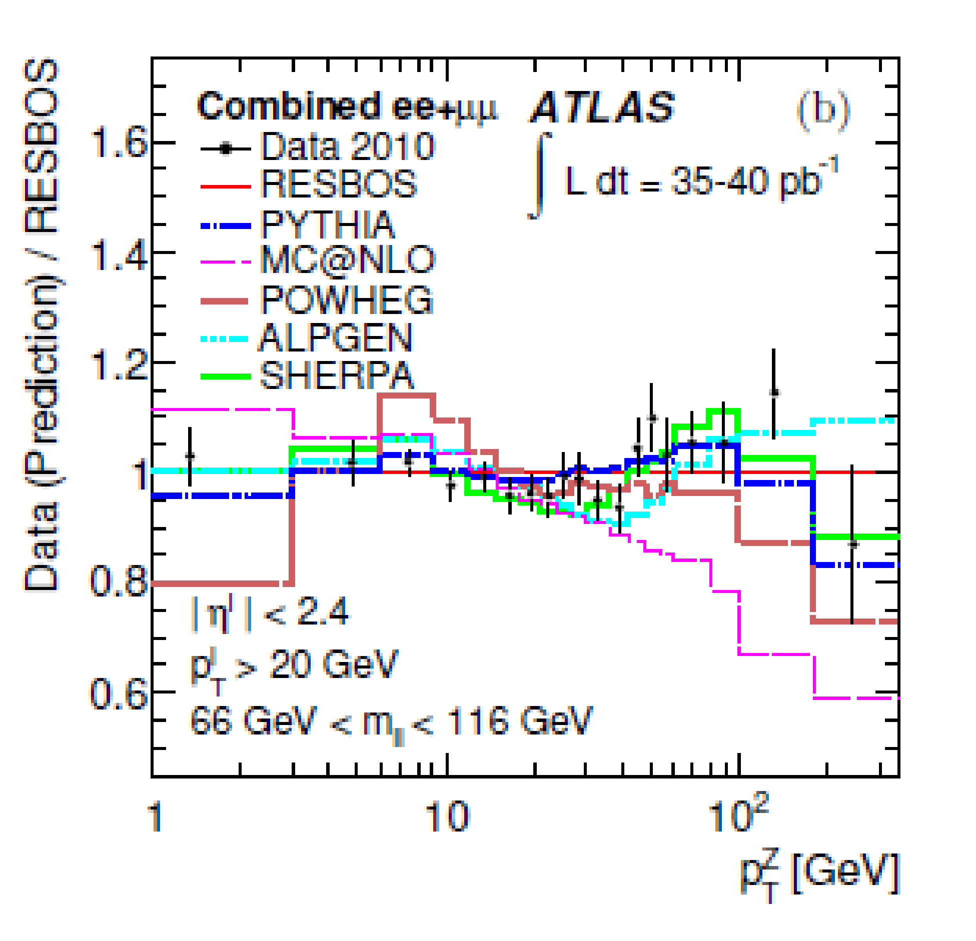
- **MORE THEORY COMPARISONS:ATLAS(1107.2381)**



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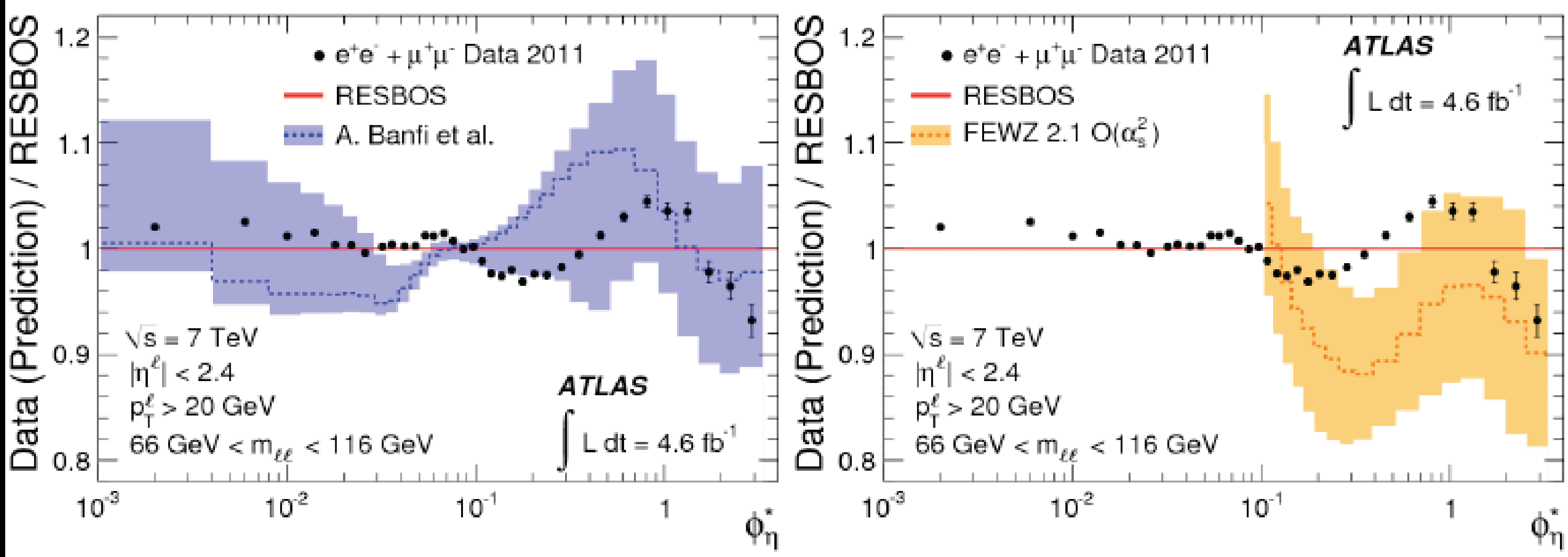
- **MORE THEORY COMPARISONS:Hassani(EW Moriond, 2013) – { $\phi^*_\eta = \tan(\frac{1}{2}(\pi - \Delta\phi))\sin\theta^*$ }**

Z/γ* transverse momentum (dσ/dφ*$_\eta$(ll))



- Calculations from A. Banfi et al. (resummed QCD predictions+fixed-order pQCD) is less good than ResBos
- **Measurement precision about one order of magnitude lower than the present theoretical uncertainties**
- FEWZ predictions undershoot the data by ~10% which confirm previous CDF observation (PRD 86,052010)

Near Future

* Herwig++(soon, running , under cross checks)
* Pyhtia 8,6 (w consultation from Peter Skands and Torbjorn Sjostrand
* Sherpa (w consultation from Jan Winter)

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Near Future

*New Observables: ϕ_η^* (w p_T cuts, etc.)

*New Data: ATLAS & CMS,

EACH > 10^7 lepton pairs

$\Longrightarrow$ COMPLETE INTRINSIC P_T TESTS

*HERWIRI2.0 (w S.Yost, M. Hjena, V. Halyo)

HERWIG6.5 $\cup$ KK MC 4.22

KK MC 4.22 (w S. Jadach, Z.Was), 1307.4037

. . . *MC@NNLO

KK MC 4.22

v_{max}	$KKsem$ Refer.	$\mathcal{O}(\alpha^3)_{EEX3}$	$\mathcal{O}(\alpha^2)_{CEEX}$ intOFF	$\mathcal{O}(\alpha^2)_{CEEX}$
	$\sigma(v_{max})$ [pb]			
0.01	0.9145 ± 0.0000	0.9150 ± 0.0004	0.9150 ± 0.0004	0.9323 ± 0.0004
0.10	1.0805 ± 0.0000	1.0807 ± 0.0004	1.0808 ± 0.0004	1.0920 ± 0.0004
0.30	1.1612 ± 0.0000	1.1615 ± 0.0004	1.1616 ± 0.0004	1.1691 ± 0.0004
0.50	1.1974 ± 0.0000	1.1977 ± 0.0004	1.1981 ± 0.0004	1.2036 ± 0.0004
0.70	1.2310 ± 0.0000	1.2312 ± 0.0004	1.2317 ± 0.0004	1.2357 ± 0.0004
0.90	1.6104 ± 0.0000	1.6128 ± 0.0003	1.6114 ± 0.0004	1.6148 ± 0.0004
0.99	1.6218 ± 0.0000	1.6254 ± 0.0003	1.6244 ± 0.0004	1.6277 ± 0.0004
	$A_{FB}(v_{max})$			
0.01	0.5883 ± 0.0000	0.5883 ± 0.0005	0.5883 ± 0.0005	0.6033 ± 0.0005
0.10	0.5882 ± 0.0000	0.5881 ± 0.0004	0.5881 ± 0.0004	0.5966 ± 0.0004
0.30	0.5879 ± 0.0000	0.5879 ± 0.0004	0.5879 ± 0.0004	0.5932 ± 0.0004
0.50	0.5875 ± 0.0000	0.5874 ± 0.0004	0.5875 ± 0.0004	0.5912 ± 0.0004
0.70	0.5848 ± 0.0000	0.5845 ± 0.0004	0.5846 ± 0.0004	0.5868 ± 0.0004
0.90	0.4736 ± 0.0000	0.4722 ± 0.0003	0.4728 ± 0.0003	0.4748 ± 0.0003
0.99	0.4710 ± 0.0000	0.4691 ± 0.0003	0.4697 ± 0.0003	0.4716 ± 0.0003

TABLE II. Study of total cross section $\sigma(v_{max})$ and charge asymmetry $A_{FB}(v_{max})$, $d\bar{d} \rightarrow \mu^-\mu^+$, at $\sqrt{s}$ =189GeV. See Table I for definition of the energy cut v_{max}, scattering angle and M.E. type,

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v=1- s'/s (EW lib. = DIZET6.21)

- Recent Progress: Cosmological Constant Λ

In Phys.Dark Univ. **2**(2013)97, using

$$B''_g(k) = \frac{\kappa^2|k^2|}{8\pi^2}\ln\left(\frac{m^2}{m^2+|k^2|}\right)$$

we show that we get the UV limit

$k^2 G_N(k) \rightarrow .0442$

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and the scalar contribution to Λ as

$$\Lambda_s = -8\pi G_N \frac{\int d^4k}{2(2\pi)^4} \frac{(2k_0^2)e^{-\lambda_c (k^2/(2m^2)) \ln(k^2/m^2+1)}}{k^2+m^2}$$
$$\cong -8\pi G_N [\frac{1}{G_N^2 64\rho^2}], \quad \rho = \ln\frac{2}{\lambda_c}$$

for $\lambda_c = \frac{2m^2}{M_{Pl}^2}$.

A Dirac fermion gives -4 times Λ_s.

$\Rightarrow$ UV limit

$$\Lambda(k) \xrightarrow[k^2\to\infty]{} k^2\lambda_*,$$
$$\lambda_* = -\frac{c_{2,eff}}{2880}\sum_j (-1)^{F_j} n_j/\rho_j^2$$
$$\cong 0.0817$$

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Comparison with EFRG(Reuter et al., Percacci et al, Litim ,….):

Illustration(Laucsher&Reuter(PRD65(2002)025013))--

UV Fixed Point:

$$\beta_\lambda(\lambda_k, g_k; \alpha, d) = -2\lambda_k + \nu_d\, d\, g_k + \left[2d(d-1+2\alpha)(4\pi\ )^{1-\frac{d}{2}}\,\Phi^2_{d/2}(0) - (d-2)\,\omega_d\right]\lambda_k\, g_k$$
$$+\frac{1}{2}d(d+1)(d-2)(4\pi)^{1-\frac{d}{2}}\omega_d\,\Phi^1_{d/2}(0)\,g_k^2 + \mathcal{O}\left(\mathrm{g}^3\right)\ ,$$

$$\beta_g(\lambda_k, g_k; \alpha, d) = (d-2)\,g_k - (d-2)\omega_d\, g_k^2 + \mathcal{O}\left(\mathrm{g}^3\right)$$

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For d=4, cut-off profile

$R^{(0)}(y) = y/(e^{y} - 1)$,

$g_* \cong \pi/(13\pi^2/144+55/24+\alpha)$

$\lambda_* \cong 3\zeta(3)/(13\pi^2/144+19/24)$

Evidently, for appropriate α and $R^{(0)}(y)$ we can have qualitative agreement with our pure gravity results

$g_* \cong 0.0533$

$\lambda_* \cong -0.000189$

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An Estimate of Λ:

Planck Scale Cosmology --

(Bonanno&Reuter(J.Phys.Conf.Series140(2008)012008))

Transition between Planck regime and classical FRW regime at

$$t_{tr} \cong 25 t_{Pl}$$

$\Rightarrow$

$$\rho_\Lambda(t_{tr}) \equiv \frac{\Lambda(t_{tr})}{8\pi G_N(t_{tr})} = \frac{-M_{Pl}^4(k_{tr})}{64} \sum_j \frac{(-1)^F n_j}{\rho_j^2}$$

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For t_{eq} = time of radiation matter equality

we get (see Branchina&Zappala (G.R.Grav.42(2010)141))

$$
\begin{aligned}
\rho_\Lambda(t_0) &\cong \frac{-M_{Pl}^4\left(1 + c_{2,eff}k_{tr}^2/(360\pi M_{Pl}^2)\right)^2}{64} \sum_j \frac{(-1)^F n_j}{\rho_j^2} \\
&\quad \times \frac{t_{tr}^2}{t_{eq}^2} \times \left(\frac{t_{eq}^{2/3}}{t_0^{2/3}}\right)^3 \\
&\cong \frac{-M_{Pl}^2(1.0362)^2(-9.197\times 10^{-3})}{64}\,\frac{(25)^2}{t_0^2} \\
&\cong (2.400\times 10^{-3} eV)^4.
\end{aligned}
$$

Compare:

$$\rho_\Lambda(t_0)|_{\text{expt}} \cong (2.368\times 10^{-3} eV(1 \pm 0.023))^4$$

CONSISTENCY CHECKS

* What About EW, QCD, GUT Symmetry Breaking Scales?

Consider GUT symmetry breaking:

It gives a $M_{GUT}^{\ 4}/(.01\ M_{Pl}^{\ 4}/64) < 10^{-6}$ correction, which we drop here.

The other breaking scales are even smaller and hence their corrections are even less significant in our result for ρ_Λ.

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CONSISTENCY CHECKS

* What About BBN Constraint?

B-R BDY CONDITION: $H(t_{tr-})=H(t_{tr+})$

$\Rightarrow$ Gauge Transformation Between Planck Scale Regime and usual FRW Regime

B-R: $t \to t' = t - t_{as} \Rightarrow \alpha/t_{tr} = 1/(2(t_{tr}-t_{as}))$

$\Rightarrow t_{as} = (1-1/(2\alpha))t_{tr}$, with $t_{tr} = \alpha/M_{Pl}$,

$\alpha = 25$.

RQG: $t \to t' = \gamma t$, as part of a dilatation $\Rightarrow$

$\alpha/t_{tr} = 1/(2\gamma t_{tr}) \Rightarrow \gamma = 1/(2\alpha)$

$\Rightarrow$

$$\Omega_\Lambda(t_{BBN}) = \frac{M_{Pl}^2(1.0362)^2 9.194\times10^{-3}(25)^2/\left(64t_{BBN}^2\right)}{(3/(8\pi G_N))\left(1/(2\gamma t_{BBN})^2\right)}$$
$$\cong \frac{\pi 10^{-2}}{24}$$
$$= 1.31\times10^{-3}.$$

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CONSISTENCY CHECKS

* What About SUSY GUTS?

Note

$$< 0|\mathcal{H}|0 > \sim \int^{M_{Pl}} \frac{d^3k}{(2\pi)^3}\frac{1}{2}\omega(k) = \int^{M_{Pl}} \frac{d^3k}{(2\pi)^3}\frac{1}{2}\sqrt{k^2+m_i^2}$$

Raises the question of GUTS: Use SO(10) SUSY GUT Approach of Dev & Mohapatra (PRD82(2010)035014):

Intermediate Stage:

$SU_{2L}xSU_{2R}xU_1XSU(3)^c$

SM Stage at ~2TeV = M_R:

$SU_{2L}XU_1XSU(3)^c$

SUSY Breaking at EW scale M_S:

$U_1XSU(3)^c$

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CONSISTENCY CHECKS

* What About SUSY GUTS?

- Possible spectrum

$$
\begin{aligned}
m_{\tilde g} &\cong 1.5(10)\text{TeV} \\
m_{\tilde G} &\cong 1.5\text{TeV} \\
m_{\tilde q} &\cong 1.0\text{TeV} \\
m_{\tilde \ell} &\cong 0.5\text{TeV} \\
m_{\tilde\chi_i^0} &\cong \begin{cases} 0.4\text{TeV}, & i=1 \\ 0.5\text{TeV}, & i=2,3,4 \end{cases} \\
m_{\tilde\chi_i^\pm} &\cong 0.5\text{TeV}, \ i=1,2 \\
m_S &= .5\text{TeV}, \ S = A^0, \ H^\pm, \ H_2;
\end{aligned}
$$

$\Longrightarrow$

$$
\Delta_{\text{GUT}} = \sum_{j\in\{\text{MSSM low energy susy partners}\}} \frac{(-1)^F n_j}{\rho_j^2} \cong 1.13(1.12)\times 10^{-2}
$$

CONSISTENCY CHECKS

* What About SUSY GUTS?

$\Longrightarrow$

- Compensate by either (A) adding new susy families with scalars lighter than fermions or (B) allowing the gravitino mass to go to $\sim .05\, M_{GUT} \sim 2\text{x}\, 10^{15}$ GeV.
- For approach (A), new quarks and leptons at $M_{High} \sim 3.4(3.3) \text{ x } 10^{3}$ TeV, scalar partners at $\sim .5$TeV $= M_{Low}$

CONCLUSIONS

* Herwiri1.031 Just as General Herwig6.5, No Tweaking, Should Be Better in IR Due to Bloch-Nordsiek Effect – Await New Data

* Real Progress on Λ in QFT (Resummed Quantum Gravity Realization of Feynman's Approach Einstein-Hilbert Theory)

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